



Quantum Capacitance Detector – progress report

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Electron Beam Lithography by
Richard E.Muller

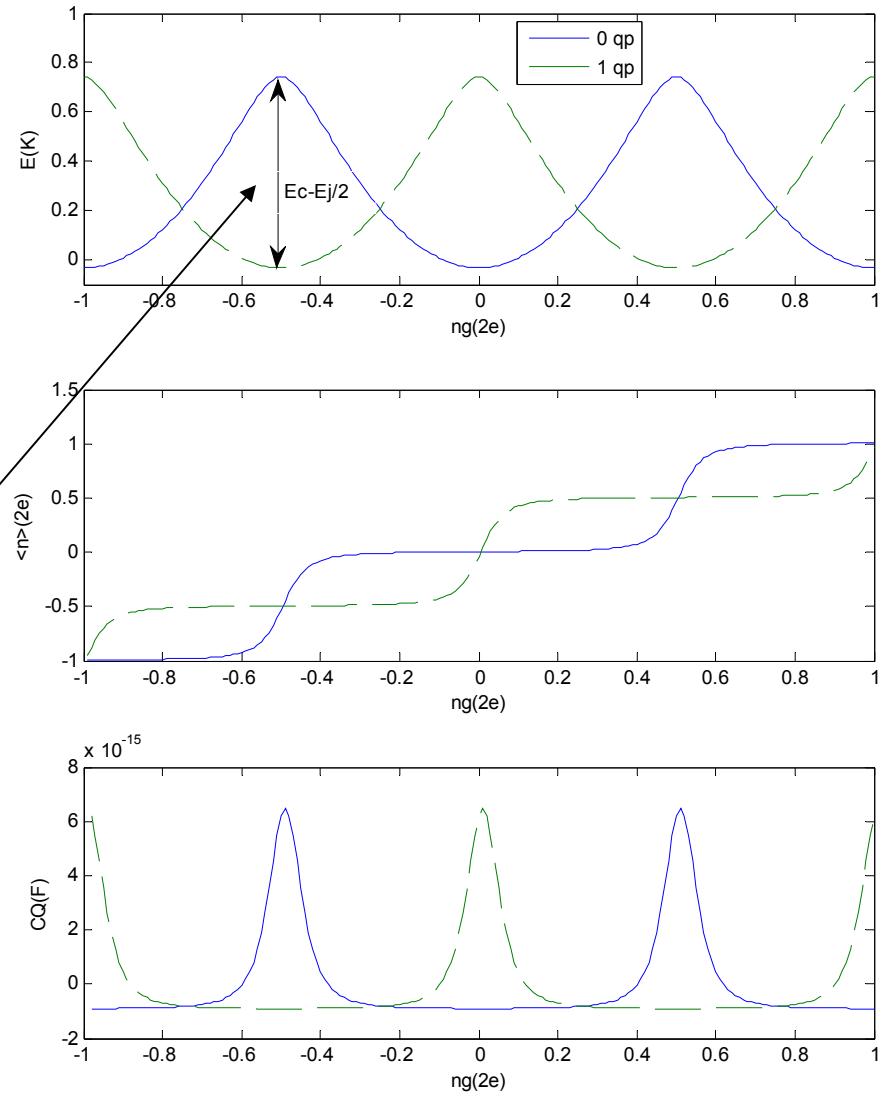
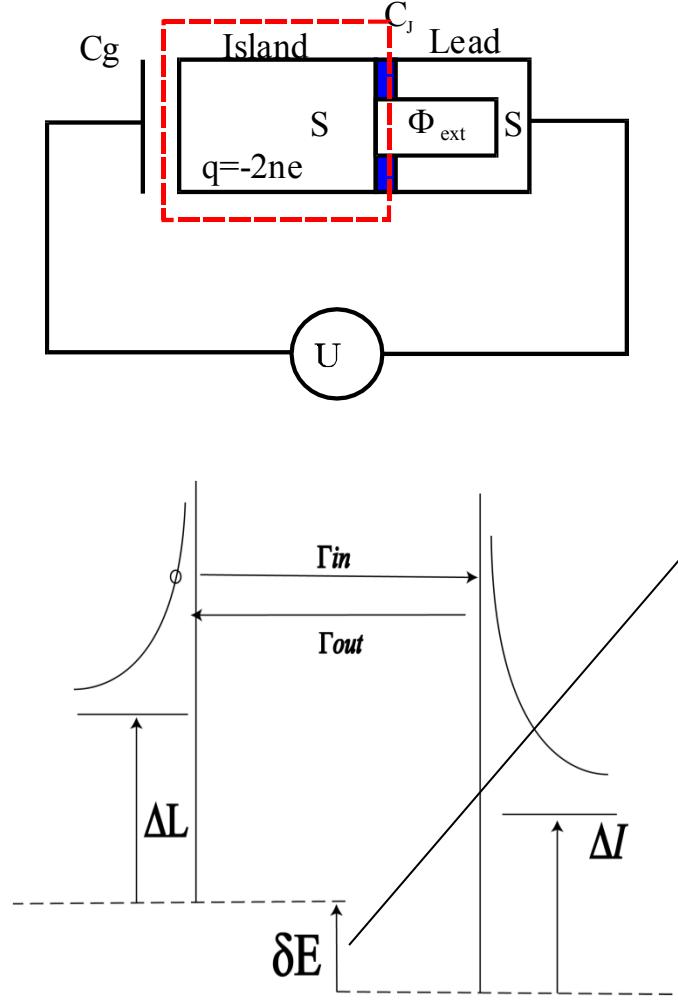
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This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

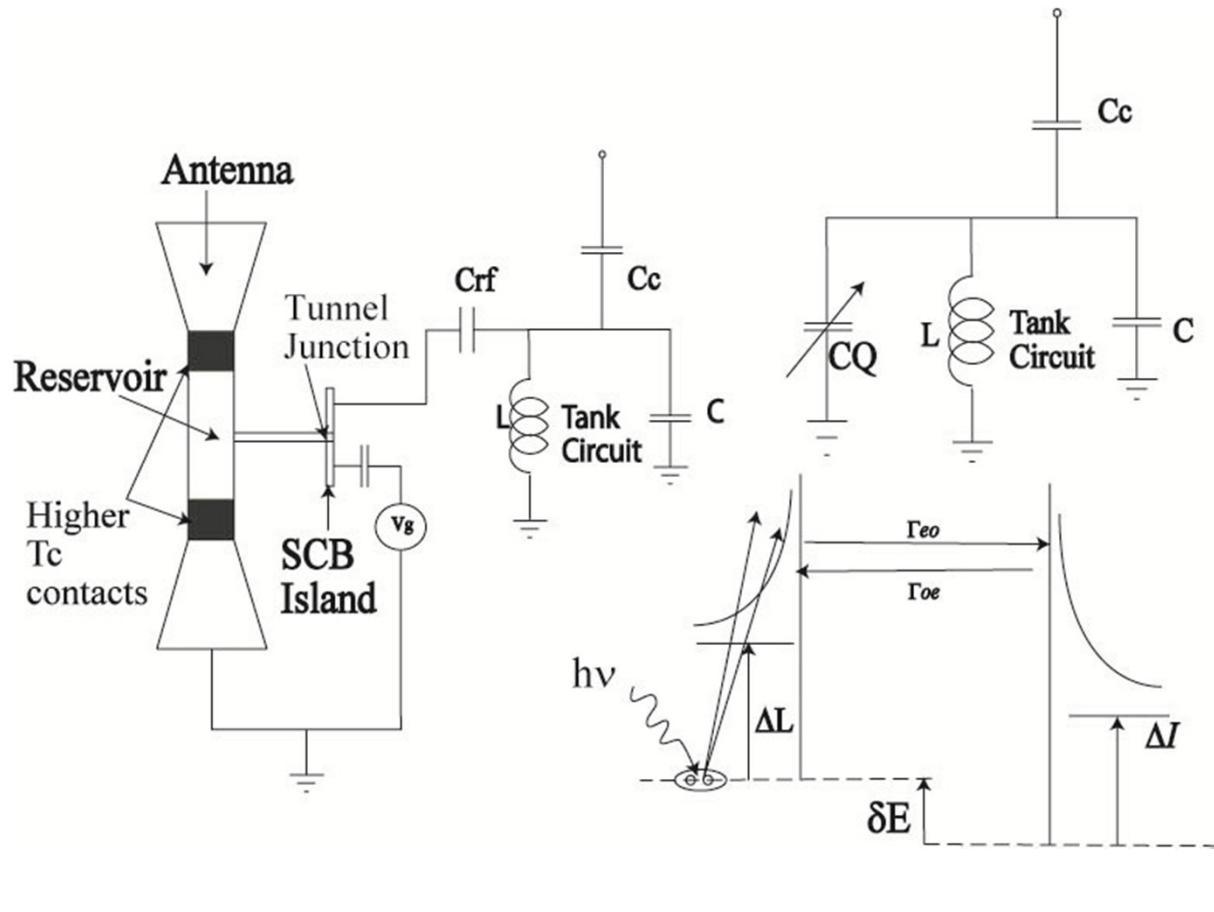


Single Cooper-pair Box (SCB)



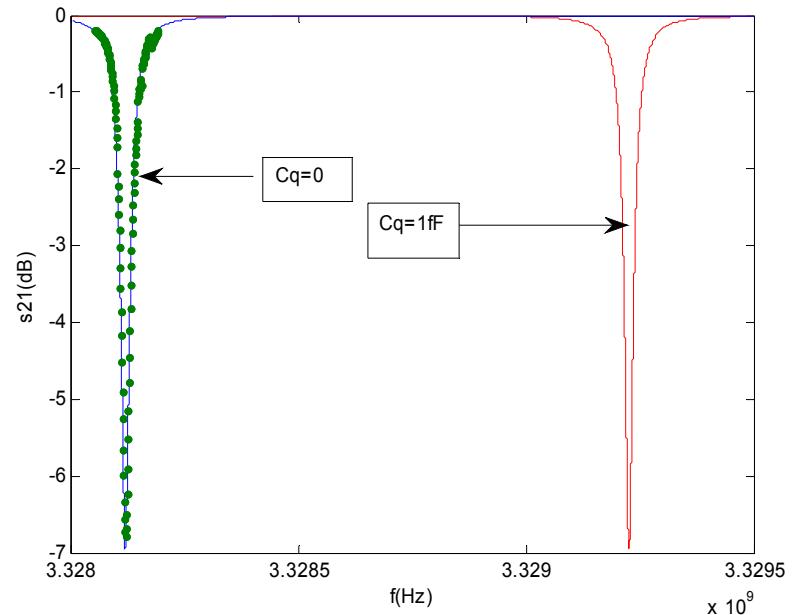
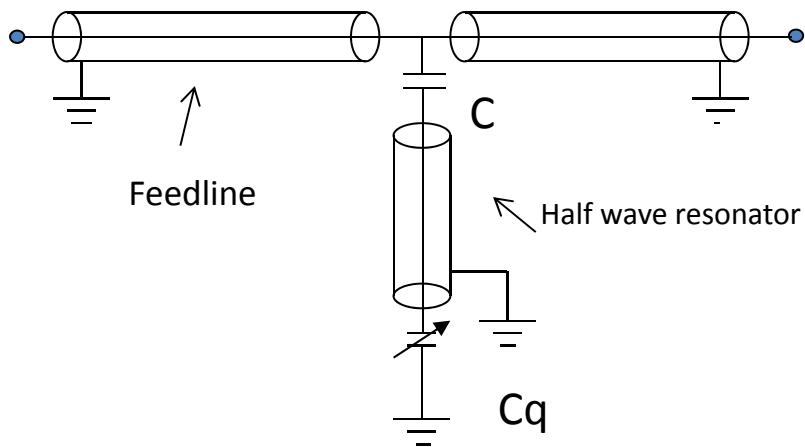


The Quantum Capacitance Detector



- Radiation coupled by an antenna breaks Cooper pairs in the reservoir (absorber)
- Quasiparticles tunnel onto the island with a rate Γ_{in} proportional to the quasiparticle density in the reservoir
- Quasiparticles tunnel out of the island with a rate Γ_{out} independent of the number of quasiparticles in the reservoir
- At steady state the probability of a quasiparticle being present in the island is given by $P_o(Nqp) = \Gamma_{in}/(\Gamma_{in} + \Gamma_{out})$
- The resulting change in the average capacitance will be $C_Q = (4E_C/E_J)(C_g^2/C_J)P_o(Nqp)$
- This change in capacitance will produce a phase shift $\delta\Phi \sim 2C_Q/(\omega_o Z_o C_C^2)$

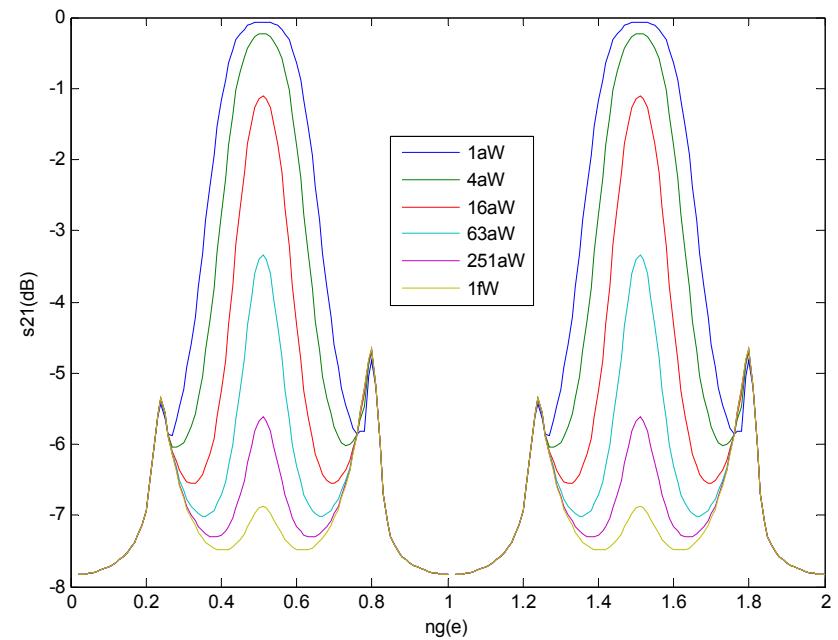
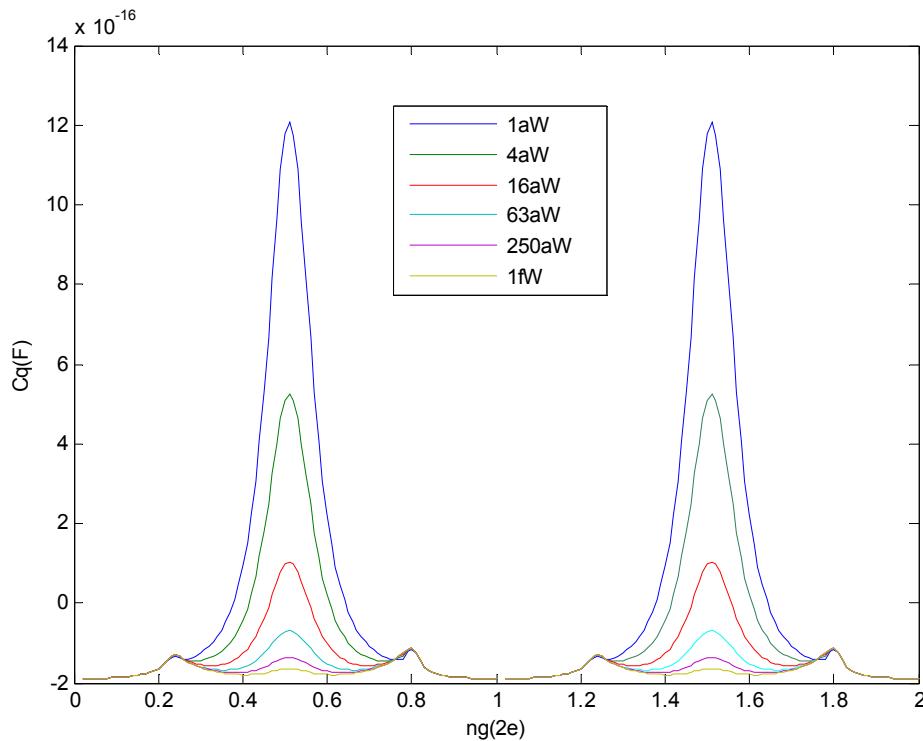
Measurement Technique



- $\lambda/2$ resonator capacitively coupled to a feedline
- SCB is the variable capacitor at the end of resonator
- Change in resonance frequency due to change in quantum capacitance should be large (1MHz)
- Single pixel resonator (green dots)
- Resonance frequency = 3.328118 GHz
- $Q_i = 220000$; $Q_c = 360000$; $Q_t = 136000$



Simulated response

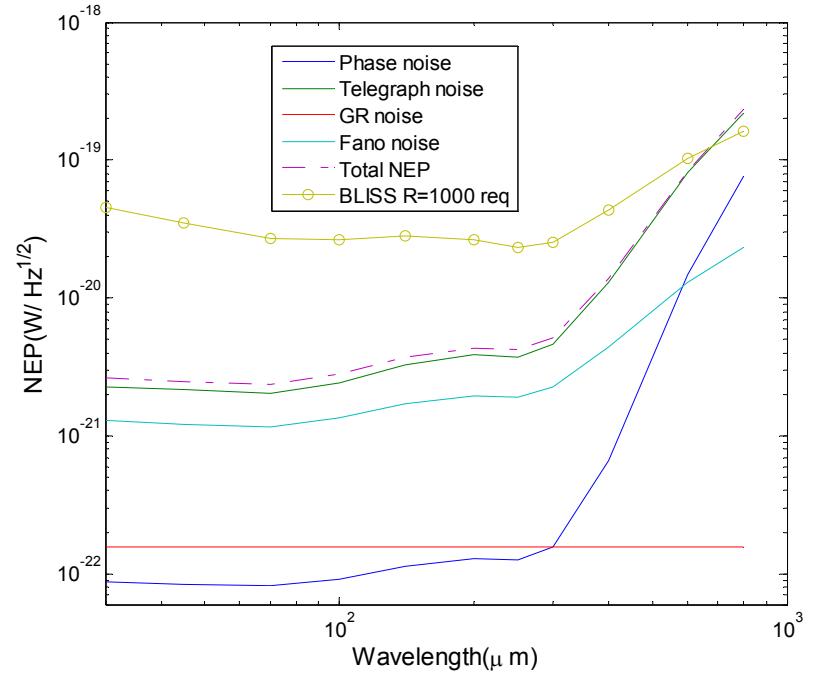
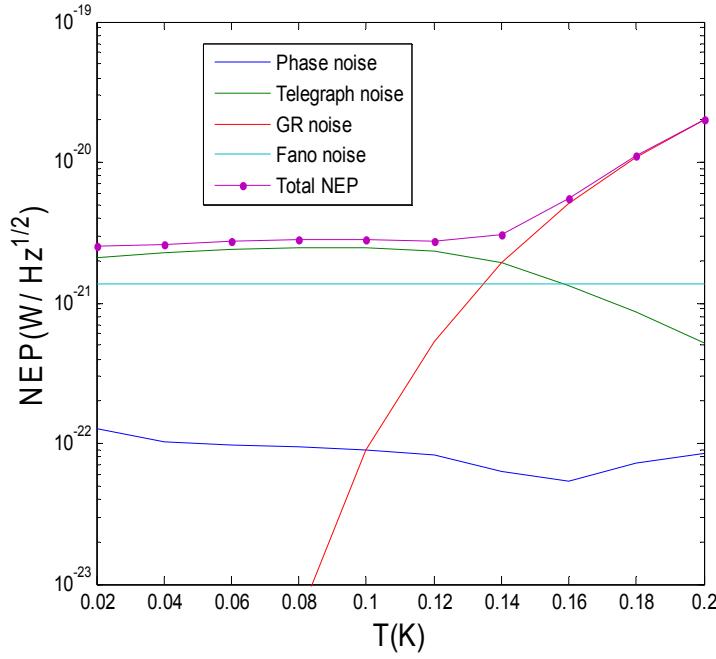


- SCB capacitance \times gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

- transmission through feedline \times gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

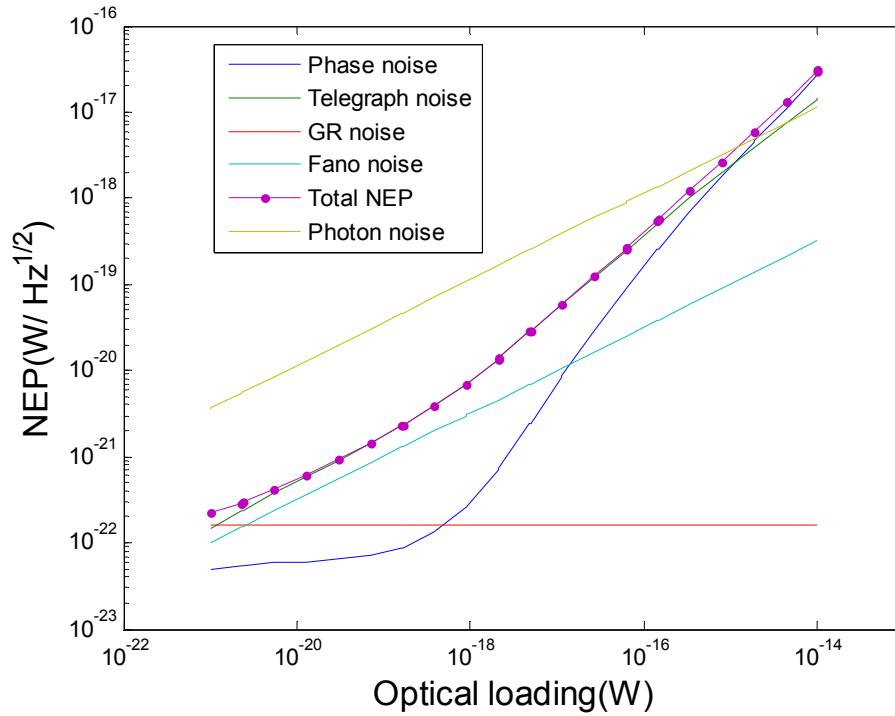


Theoretical Sensitivity

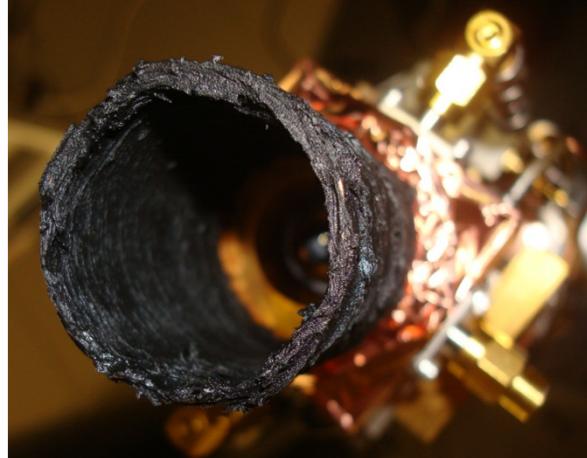


Left: NEPs from various noise sources calculated for devices optimized for $\lambda = 100\mu\text{m}$, optical loading 10^{-19} W and $R=1000$ as a function of temperature. Right: NEPs of various noise sources as a function of wavelength as compared to the requirements for a spectrometer with $R=1000$ and the expected optical loading at L2 for a cold (4.2K) telescope . The operating temperature was chosen to be 0.1K at which the GR noise contribution is negligible.

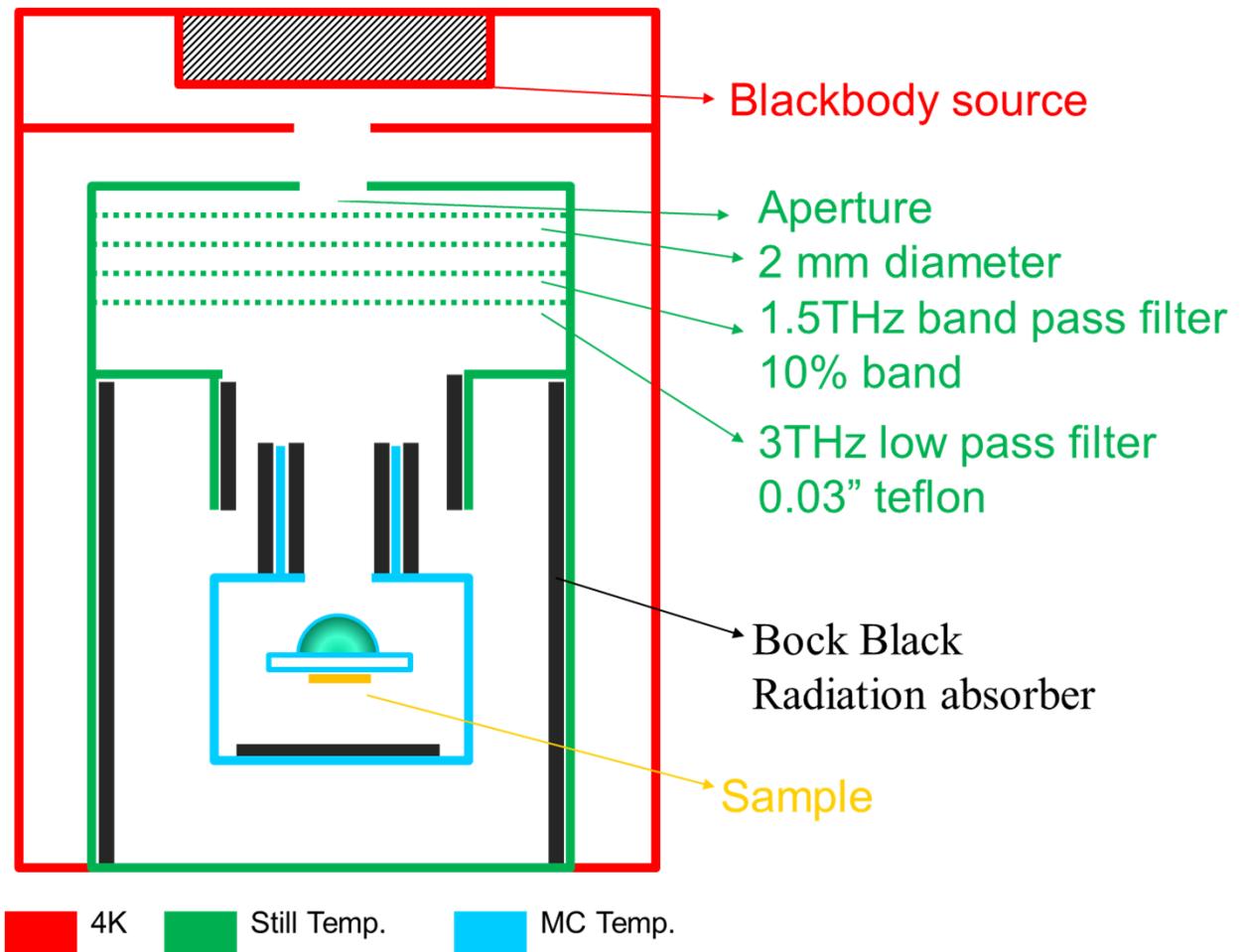
Theoretical Sensitivity vs. Signal Power



- Detector is background limited over a wide range of operation



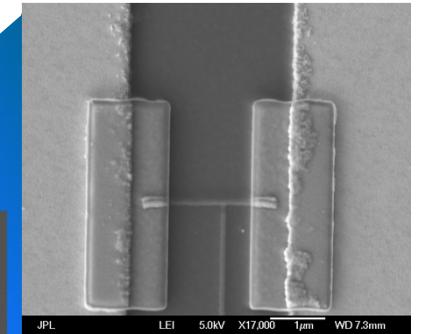
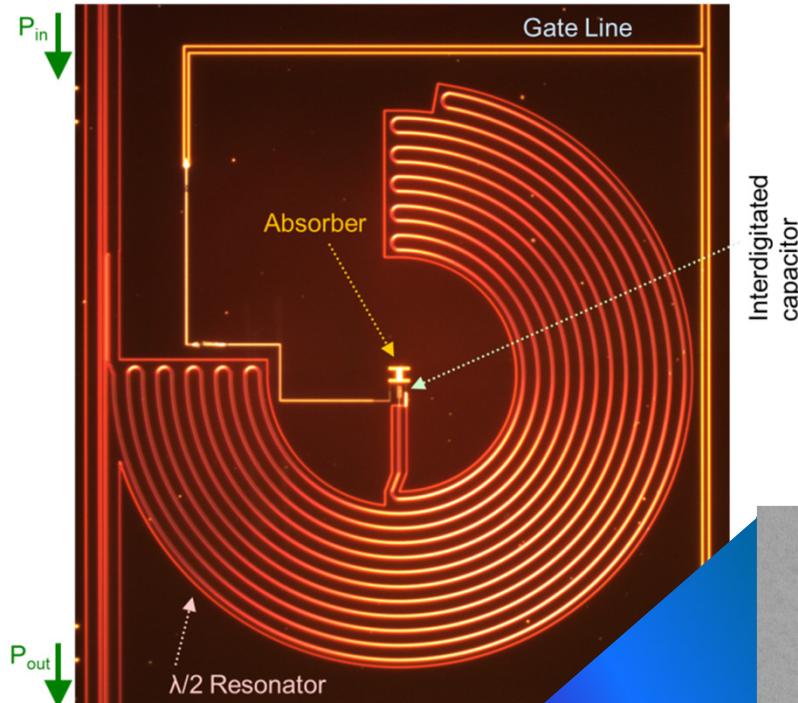
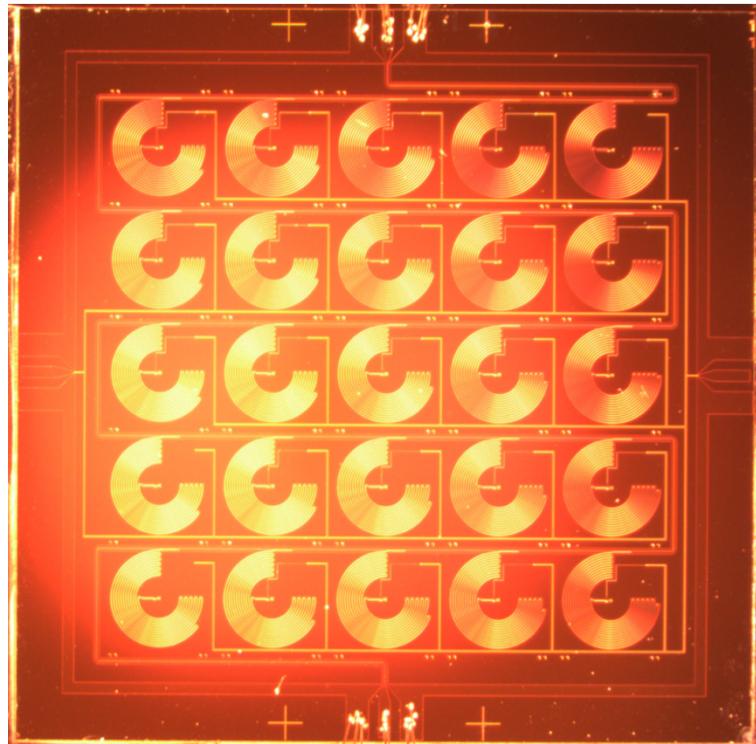
Experimental Setup



- Black body source and filters provide 1.5THz radiation from 4.2 – 40 K. Bock Black absorbs stray 4K radiation

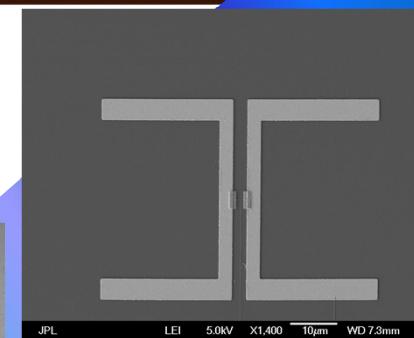
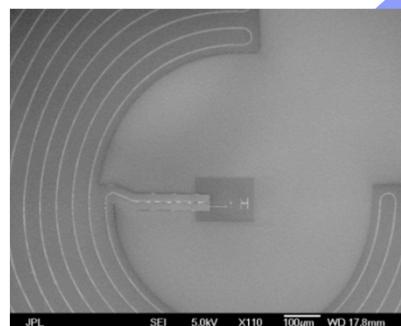


Quantum Capacitance Detector: 5x5 Array



Nb plugs

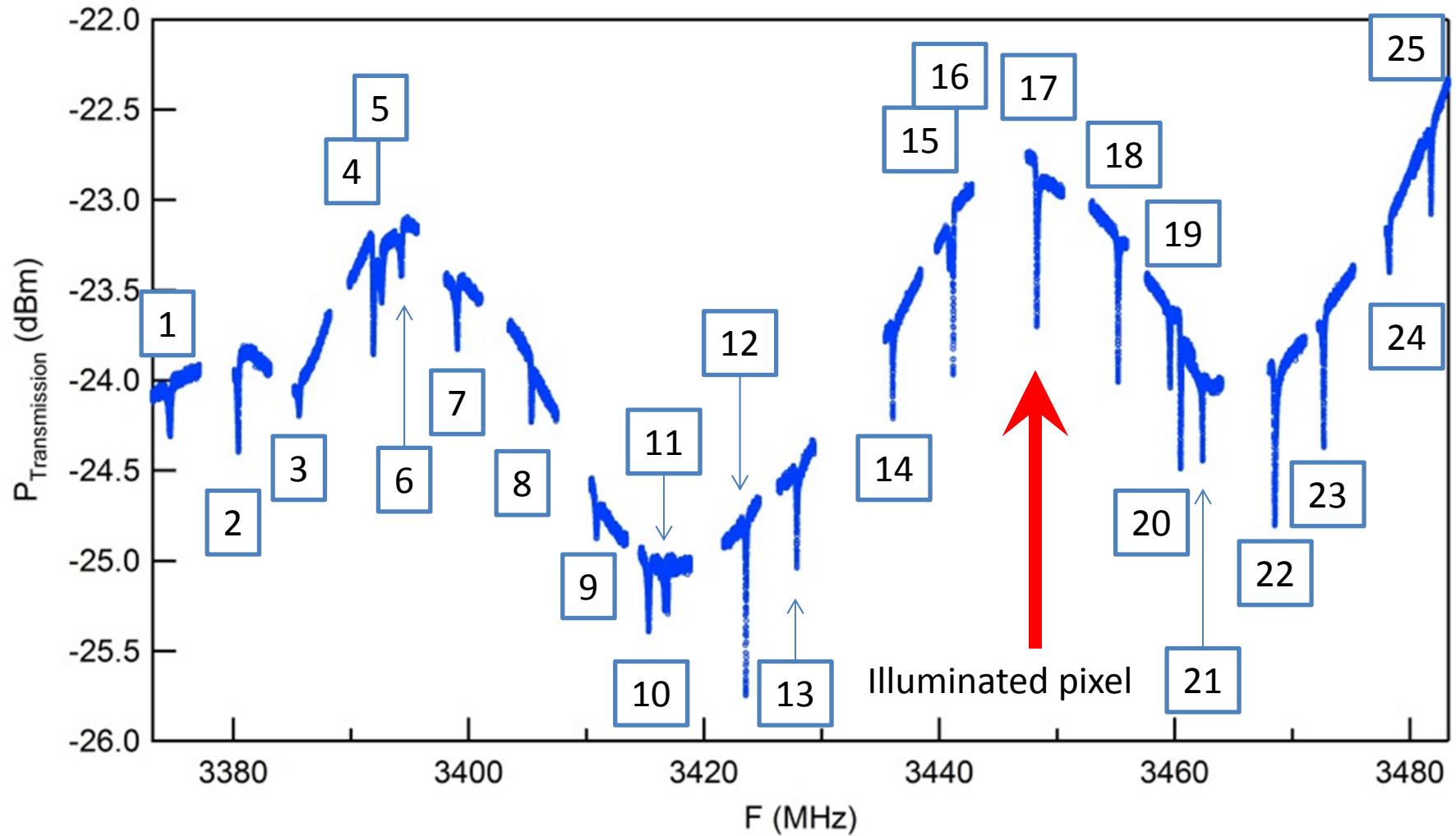
Only center device
Illuminated by lens.
Each device has a slightly
Different resonance frequency.



Au absorber



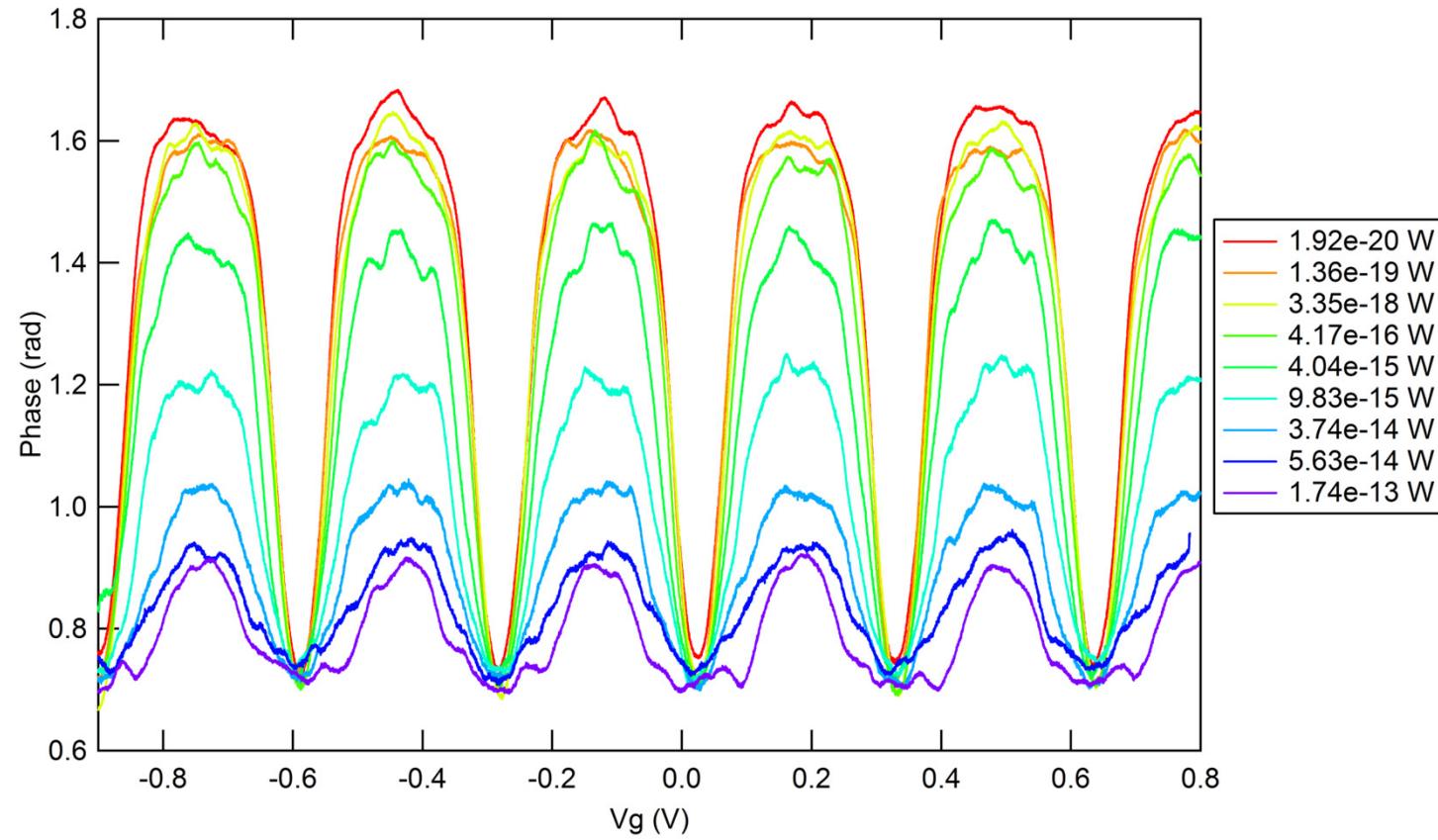
Resonances



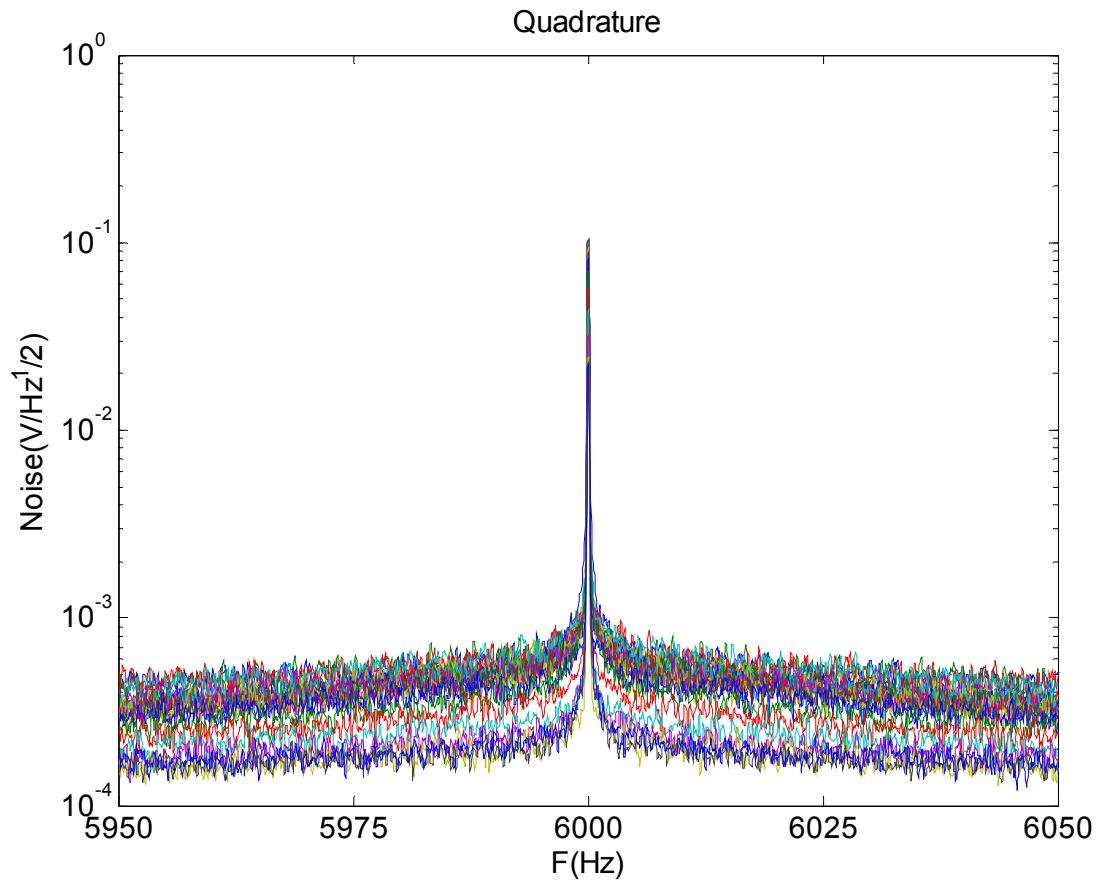
Plot of all 25 resonances, variable spacing and depth due to various coupling capacitor sizes.

This technique allows for frequency multiplexing.

Phase shift x gate voltage as a function of black body source temperature

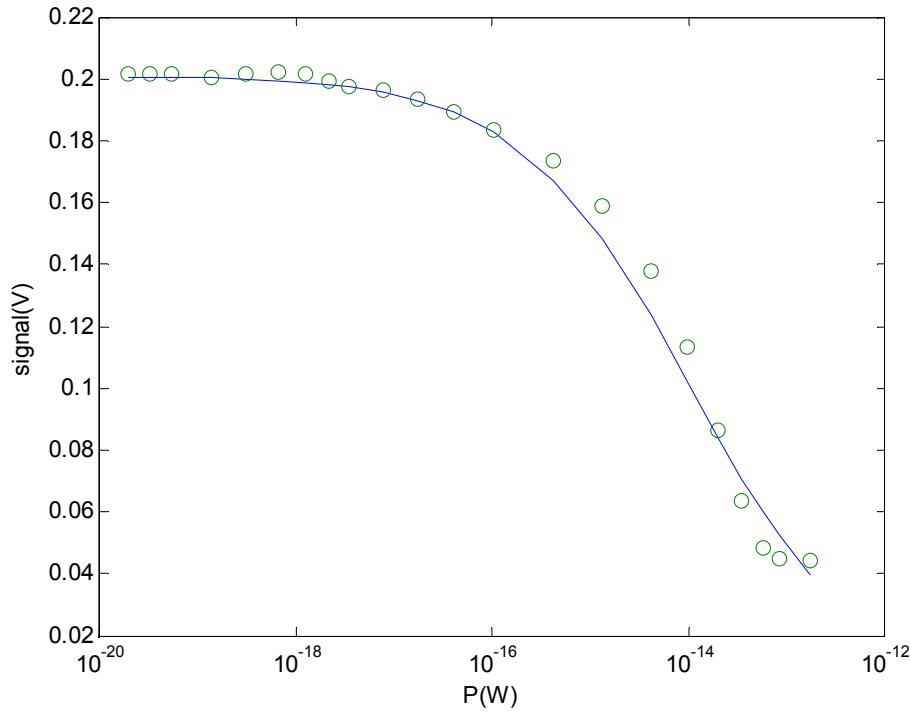


Spectrum analyzer response

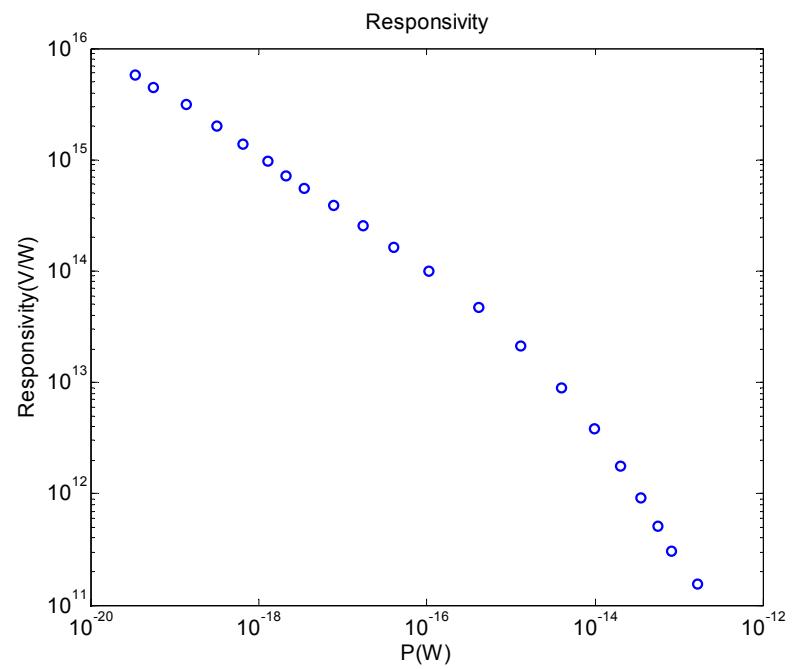


Gate voltage swept at 1kHz, spanning 6 peaks
Peak at 6kHz is the signal

Response and responsivity

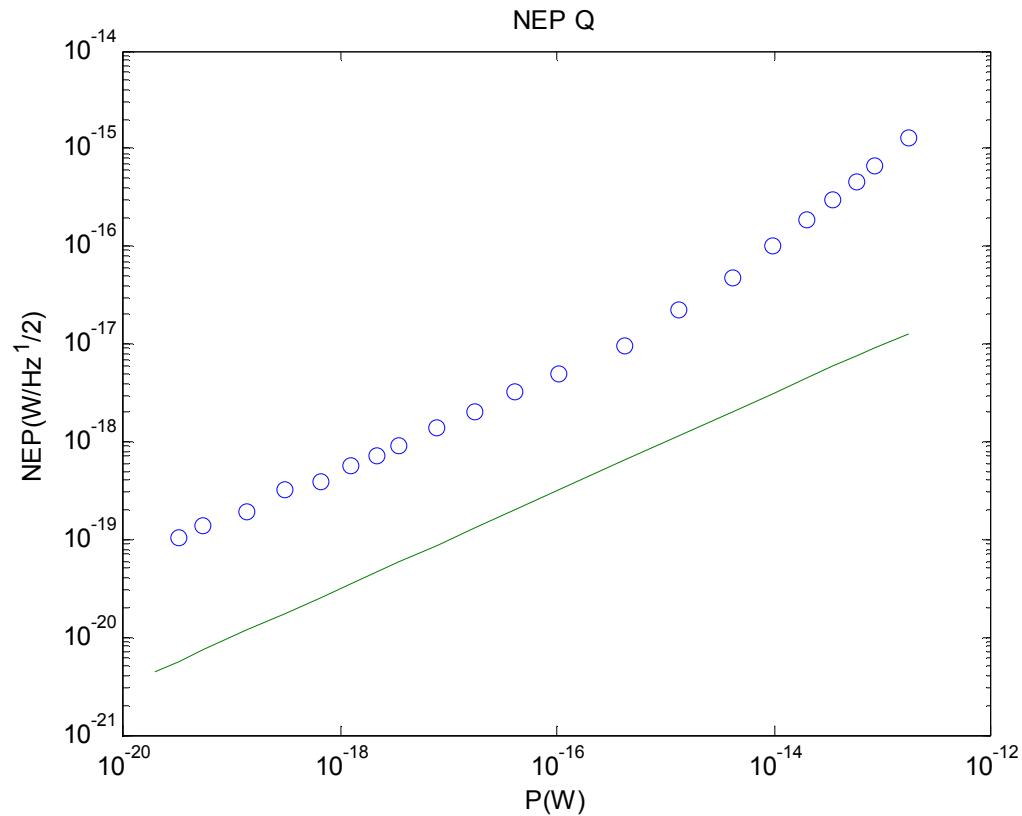


Amplitude of 6KHz peak as a function of optical signal power.
Fit comes from simulation of device based on telegraph noise measurements



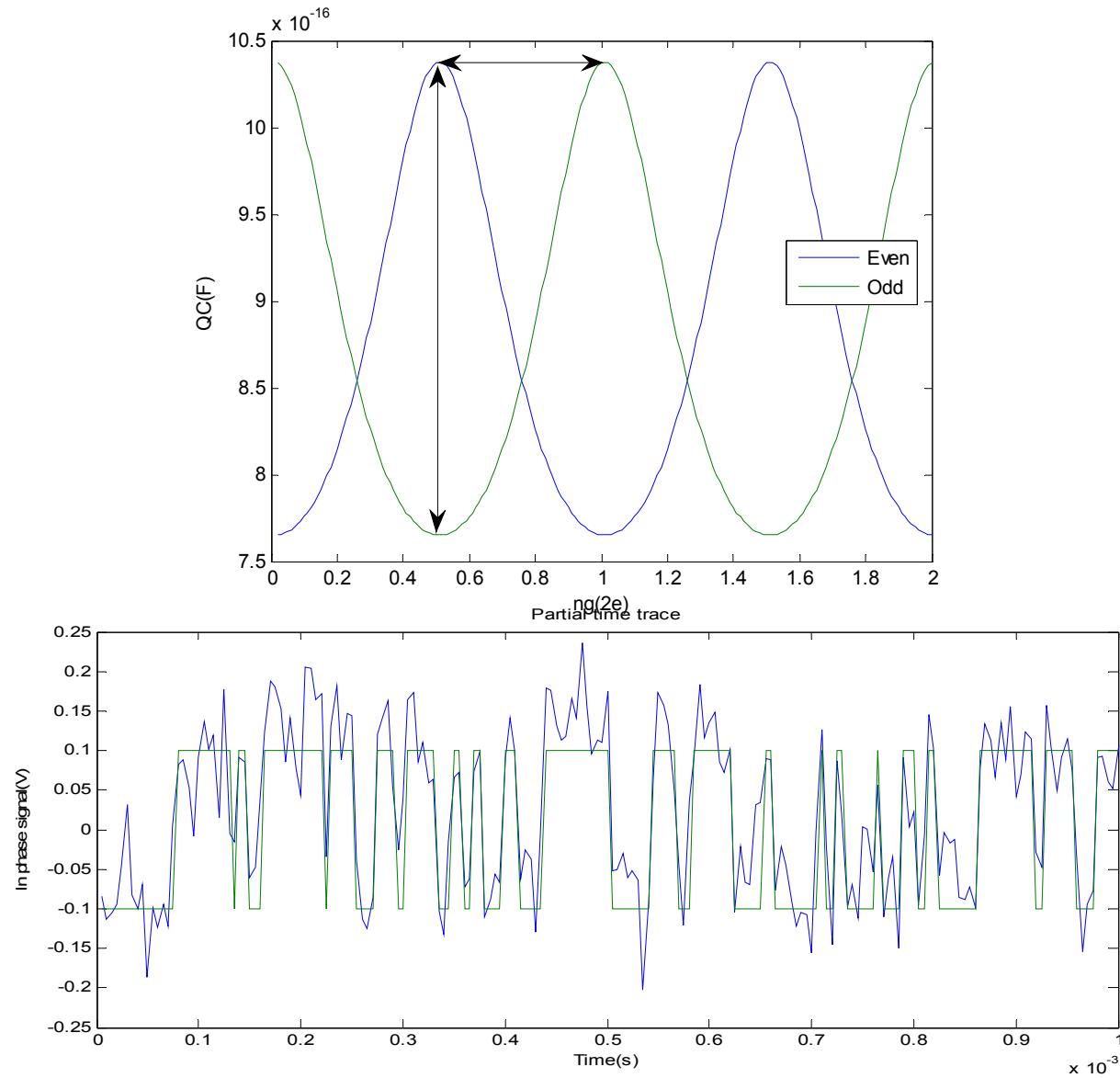
Responsivity dR/dP

Noise Equivalent Power

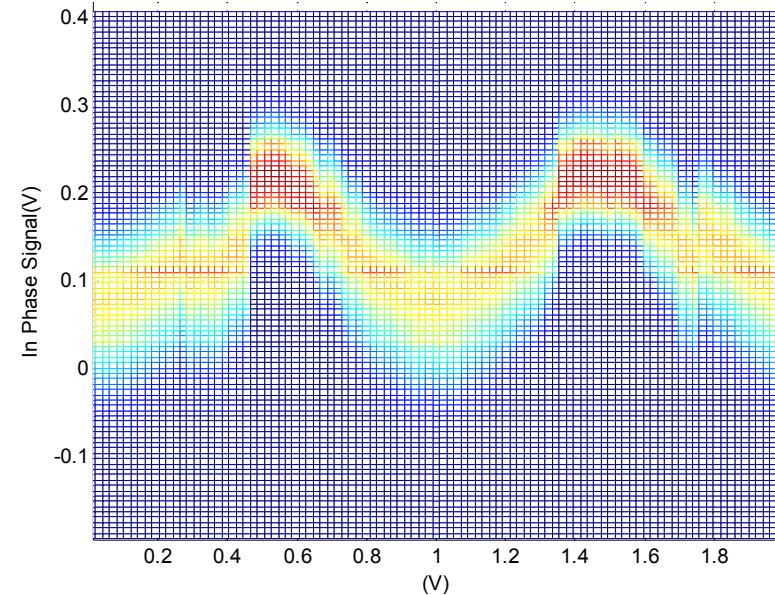
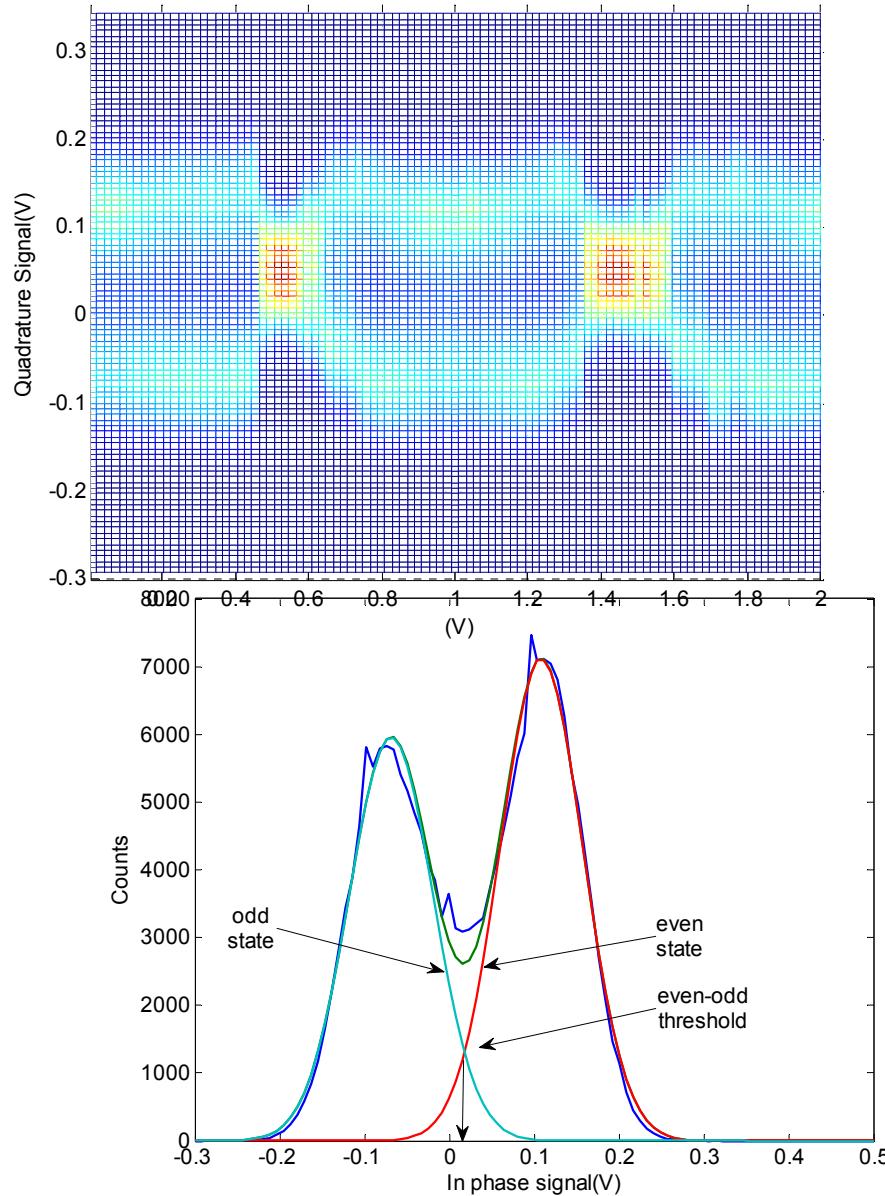




Real time measurement – telegraph noise

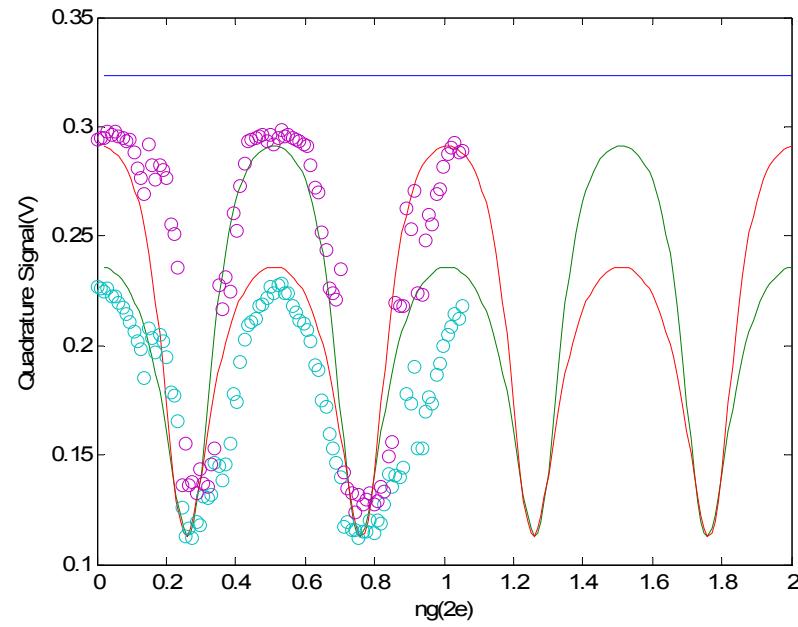
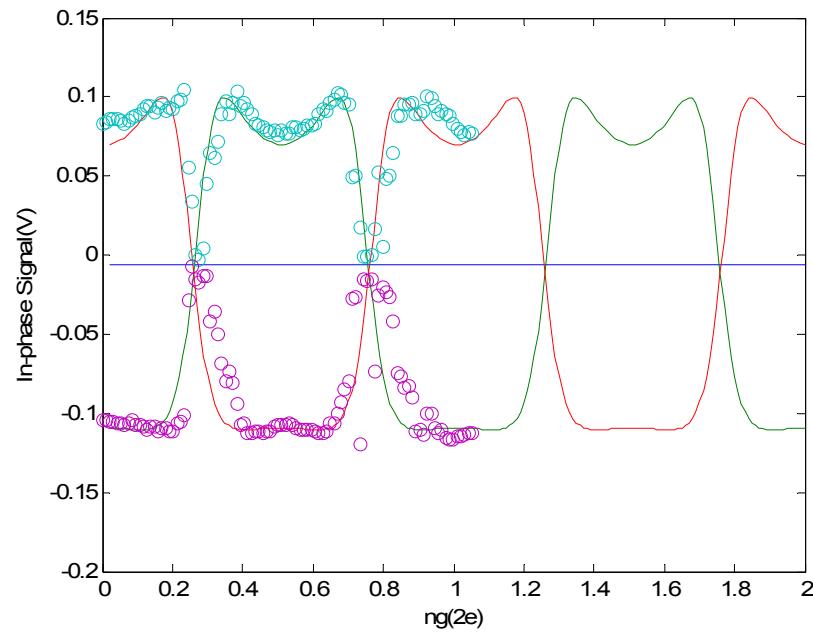


Telegraph noise histograms as a function of gate voltage



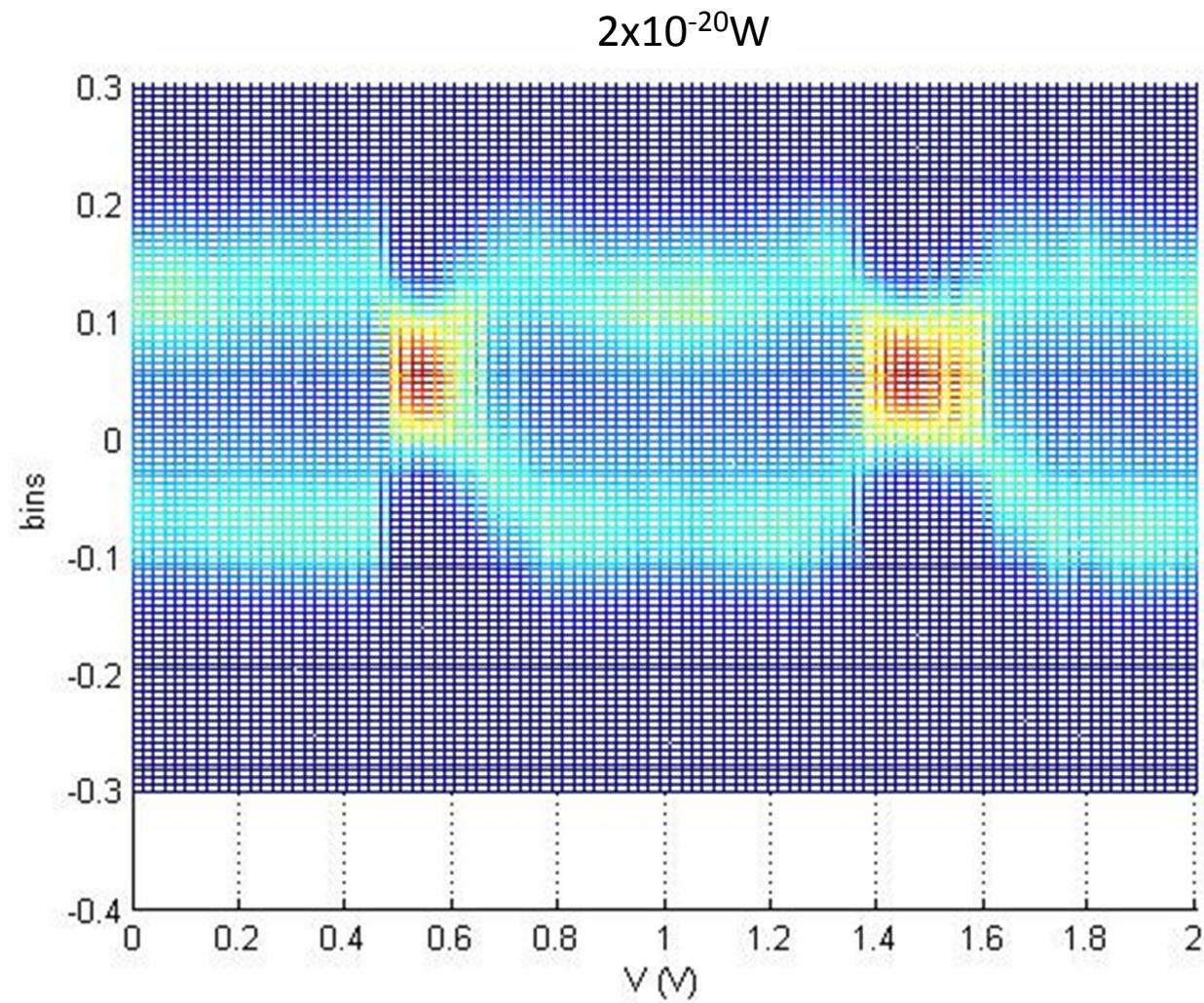
- Histogram peaks trace even and odd state traces
- Histograms fit by two gaussian

In phase and quadrature transmitted signal fits

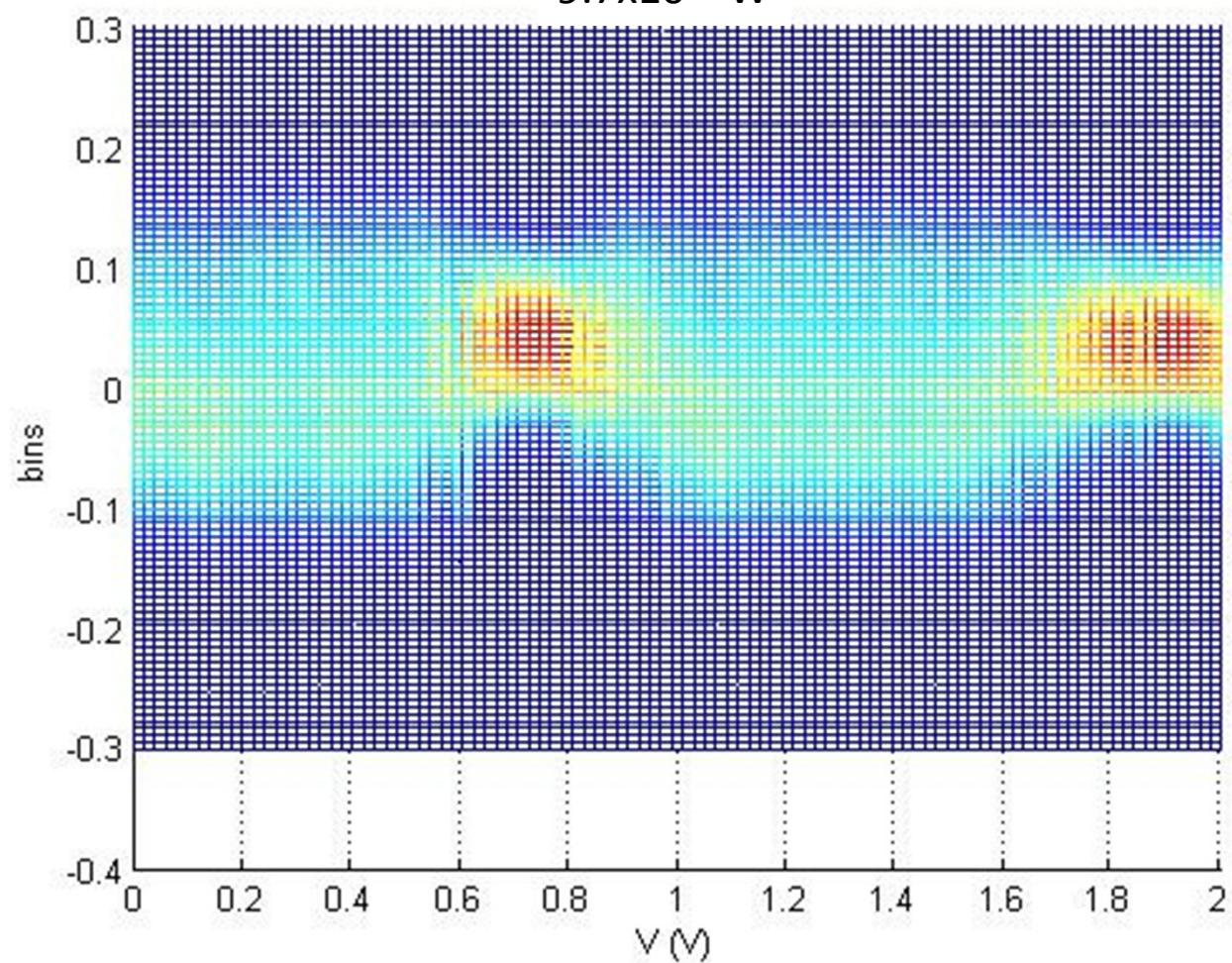


- Fits yield several parameters :
- $E_c=5.51K$, $E_J=1.4K$, $C_g= 1.26fF$, $C_J=0.55fF$
- From E_J and superconducting gap we extract $R_n=7.5k\Omega$

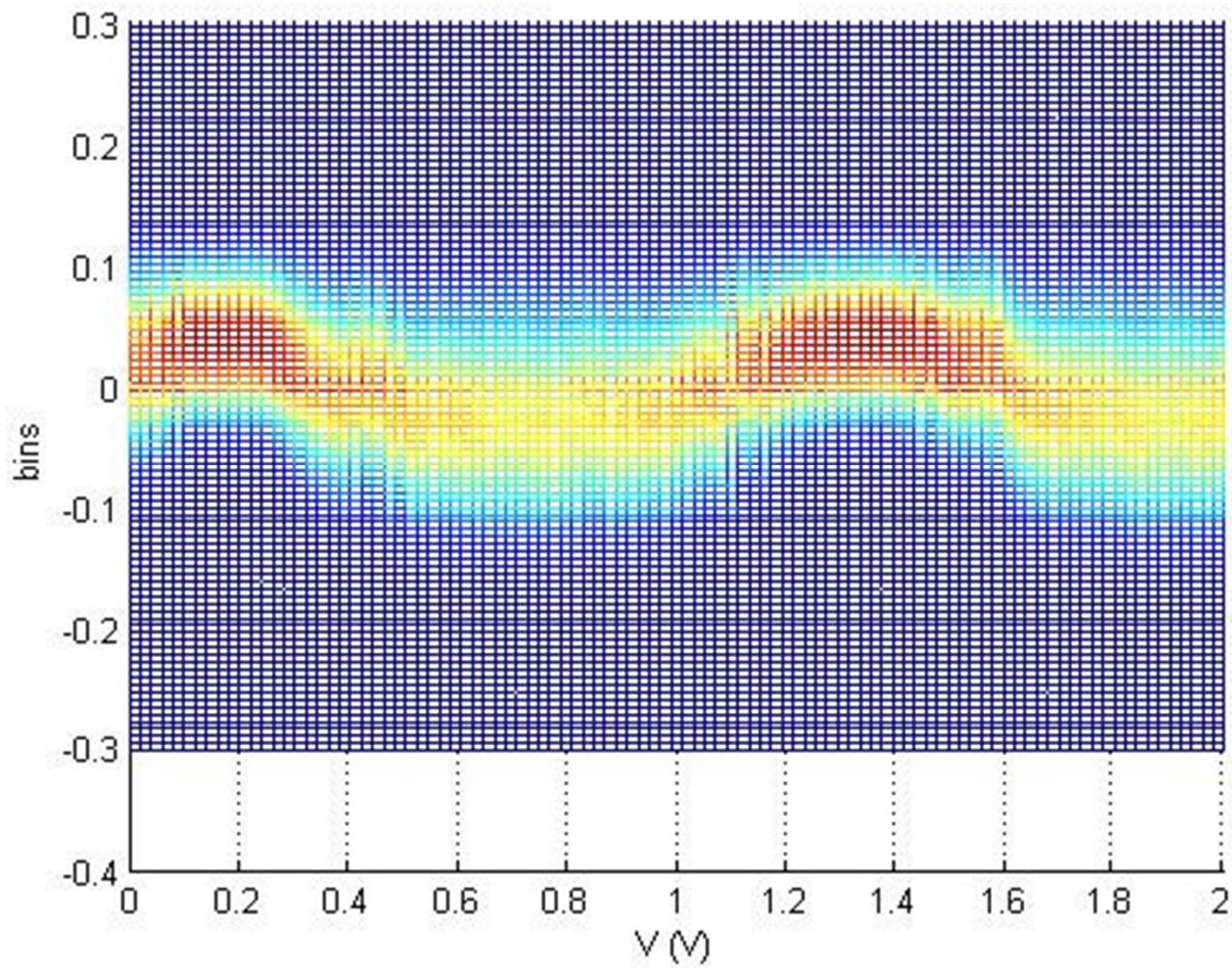
Measurements as a function of black body temperature and sample temperature



$9.7 \times 10^{-15} W$

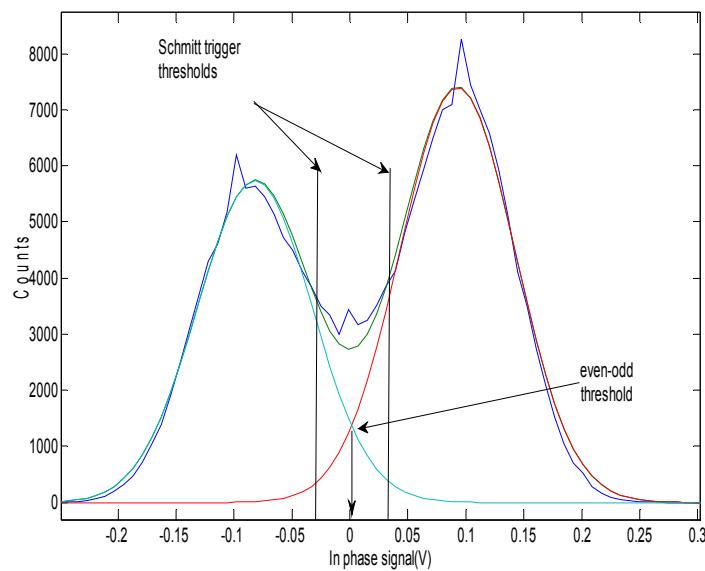
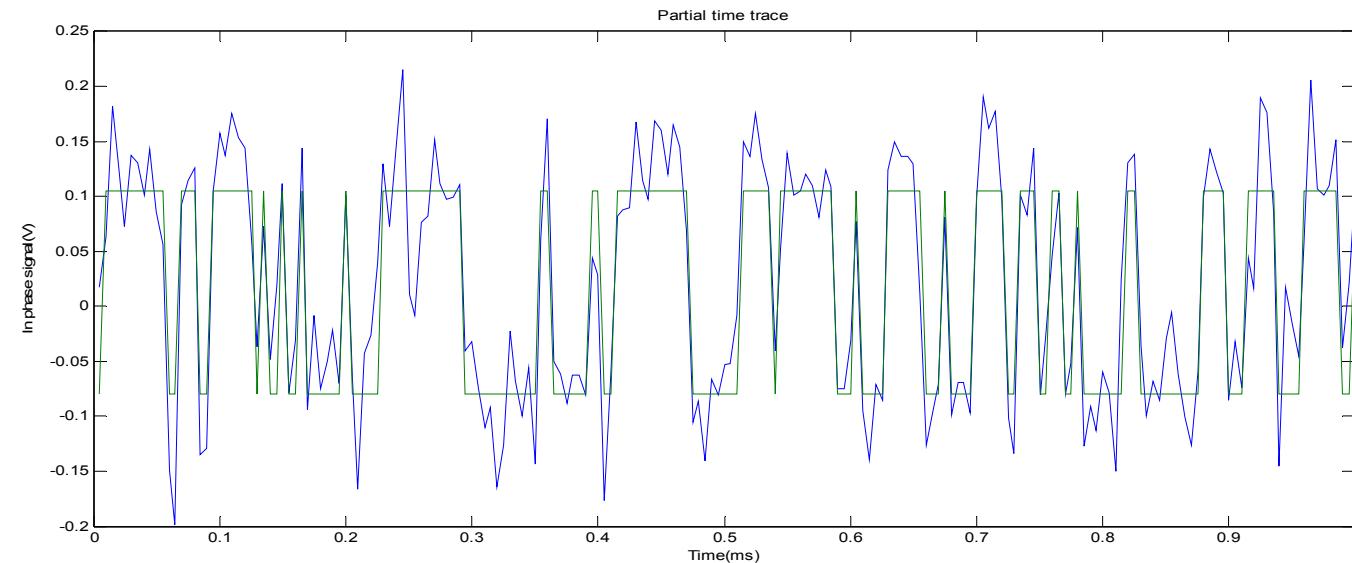


$5.6 \times 10^{-14} W$



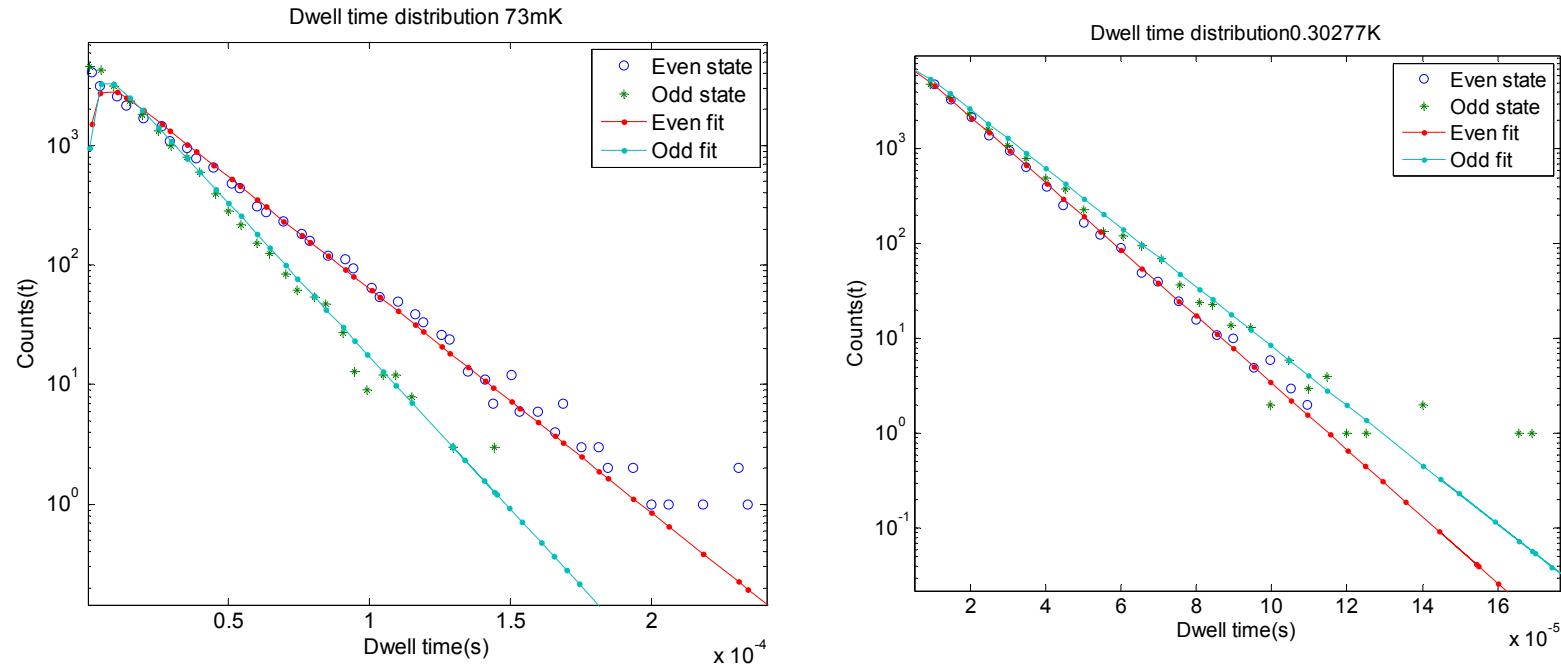


Real time measurement – telegraph noise



- Apply Schmitt trigger algorithm
- Measure dwell time distribution in even and odd state

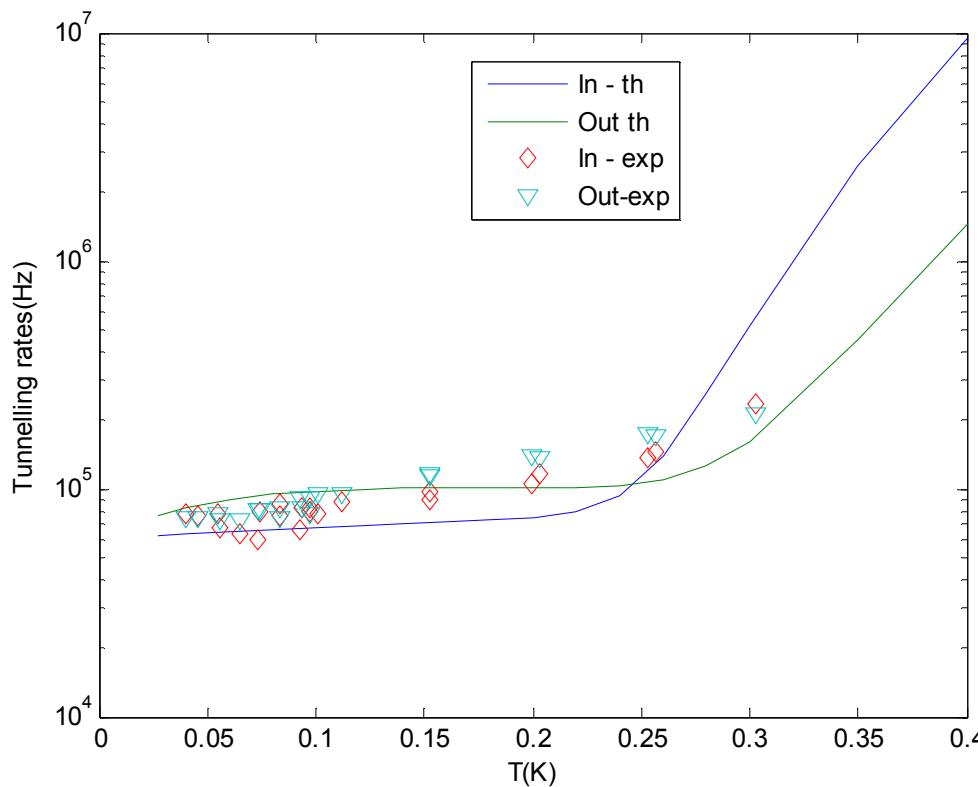
Dwell time distribution – temperature dependence



- Tunneling rates comparable to measurement time $1/\Gamma_{\text{DET}}$
- Apply procedure by Naaman and Aumentado -PRL **96**, 100201 (2006)
- Fit curves to

$$h \propto e^{-\frac{1}{2}\lambda t} \sinh\left(\frac{\theta t}{2}\right), \quad \theta = \sqrt{\lambda^2 - 4\Gamma_{\text{IN}}\Gamma_{\text{DET}}} \quad \lambda = \Gamma_{\text{DET}} + \Gamma_{\text{IN}} + \Gamma_{\text{OUT}},$$

Temperature dependence of tunneling rates



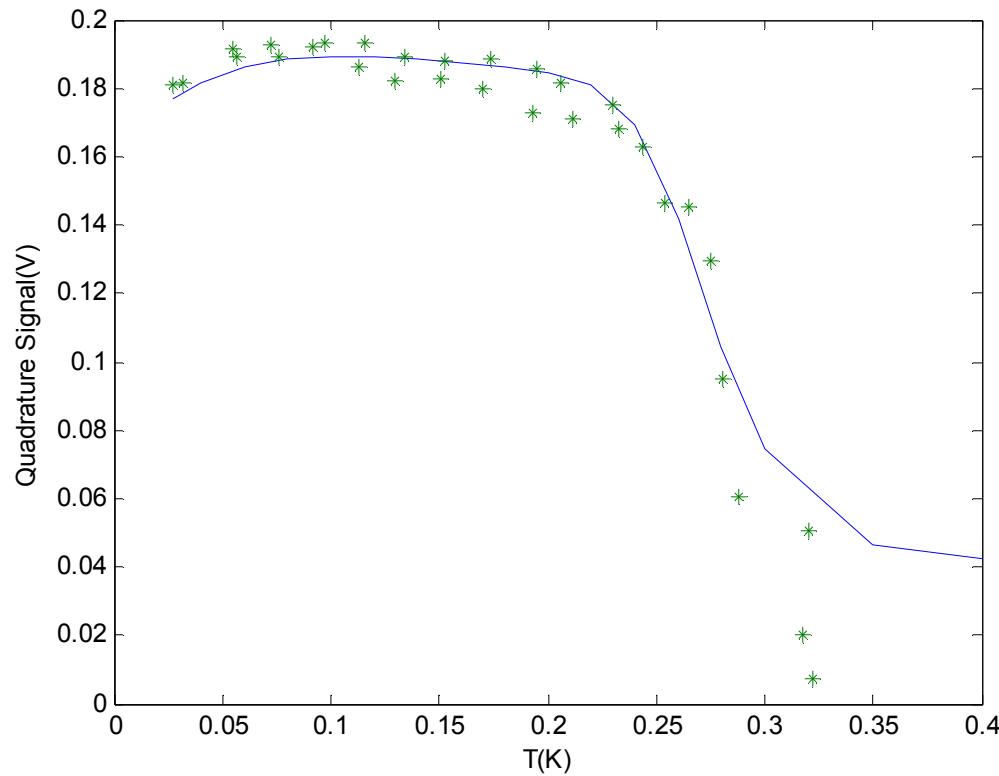
Shaw et al. PRB
79, 144511
(2009)

$$\Gamma_{IN} = n_{qp} \frac{G_N}{e^2} \frac{e^{\Delta_L/kT}}{V_L N_L} \int_{\max(\Delta_I - \delta E, \Delta_L)}^{\infty} dE \frac{E(E + \delta E) - \Delta_L \Delta_I}{\sqrt{(E + \delta E)^2 - \Delta_I^2}(E^2 - \Delta_L^2)} e^{-E/kT}$$

1890
 $\mu\text{m}^3/\text{qp}$

- low temperature flat part \rightarrow residual number of quasiparticles = $35 \text{ qp}/\mu\text{m}^3$

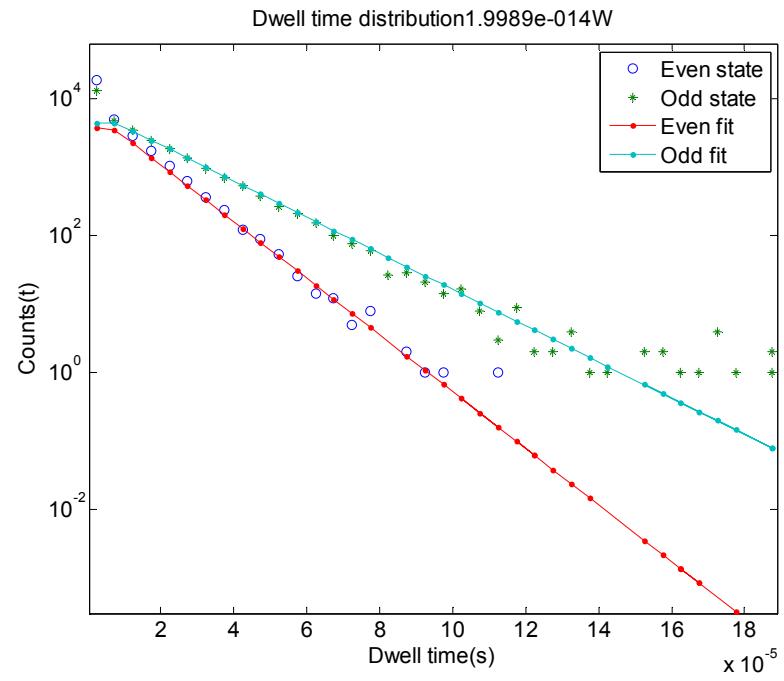
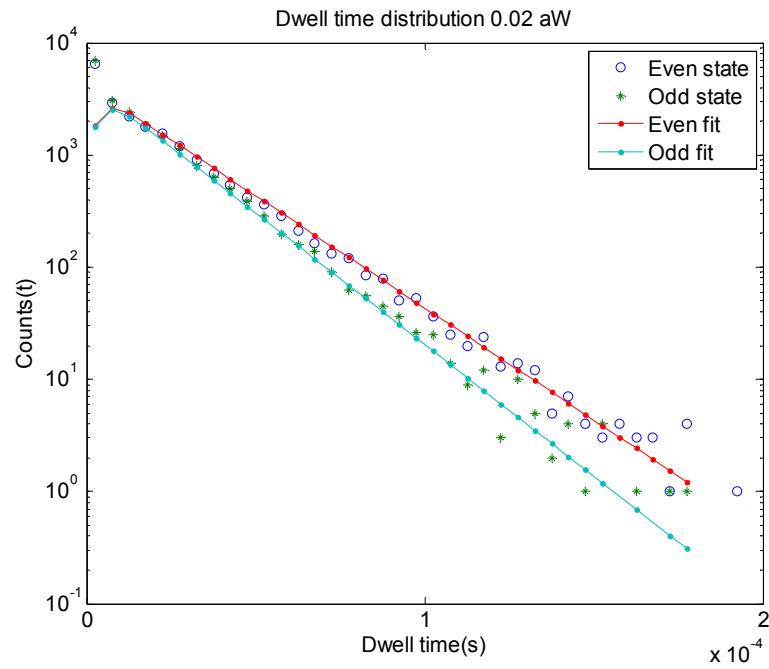
Response x temperature - fit



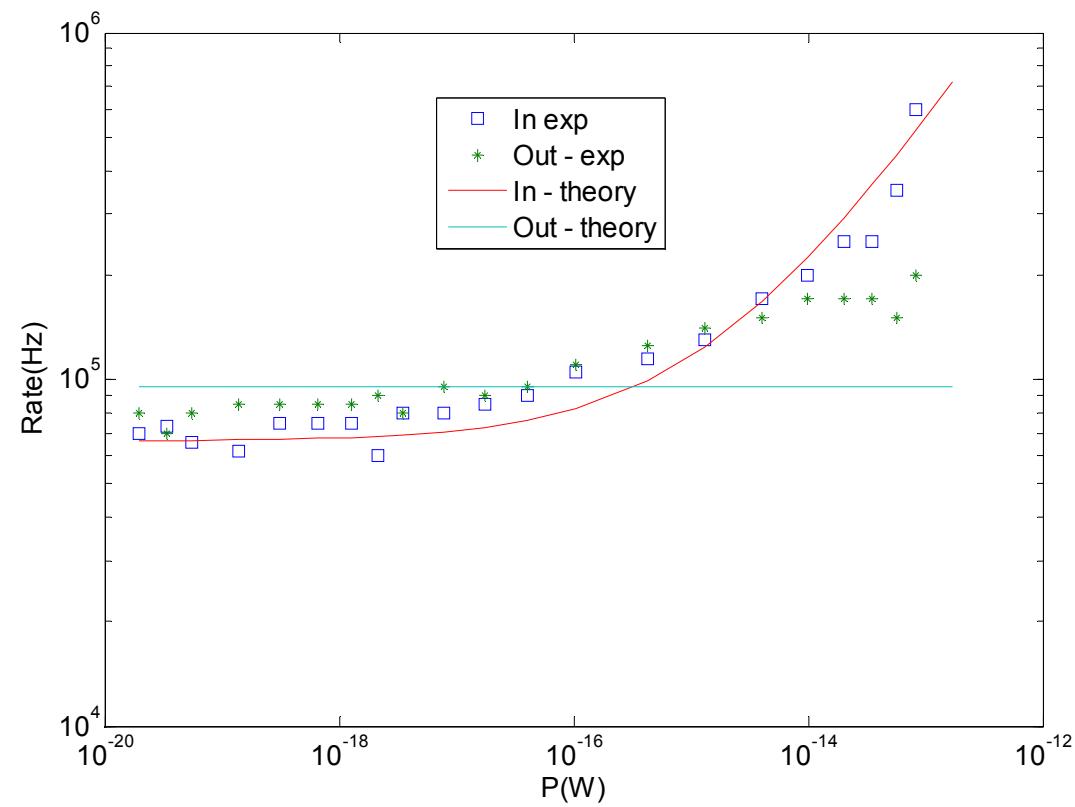
$$R = \frac{\Gamma_{OUT}}{\Gamma_{OUT} + \Gamma_{IN}} A_{EVEN}$$

- A_{EVEN} is the amplitude of the completely unpoisoned quantum capacitance response
- Assuming the amplitude of the completely poisoned state to be nearly zero

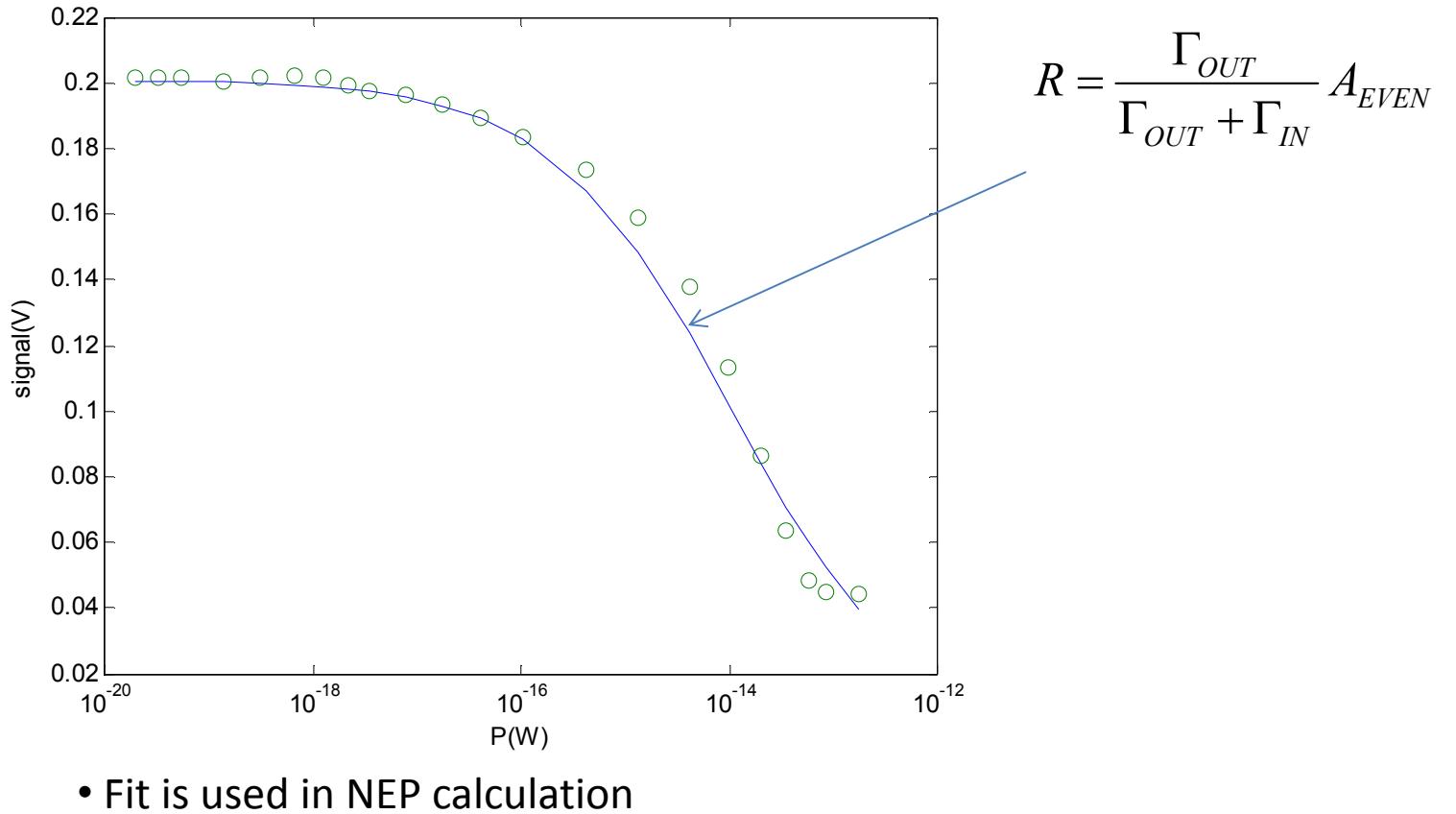
Dwell time distribution – optical power dependence



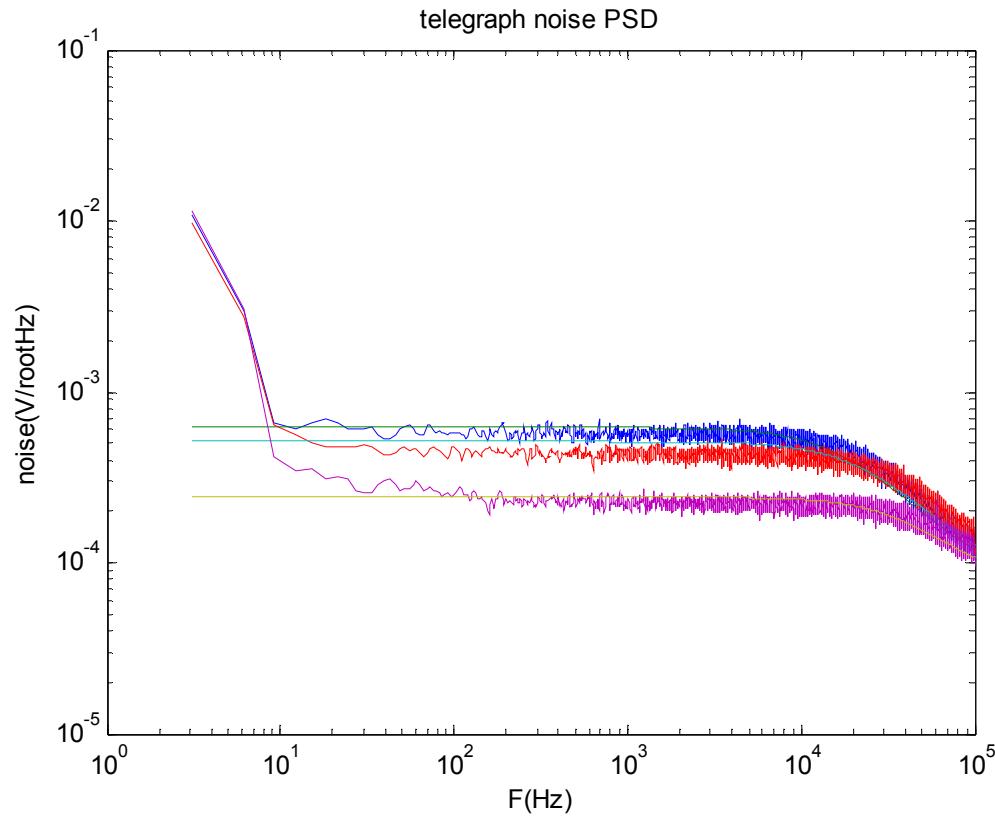
Optical power dependence of tunneling rates



Response fit using tunneling rates



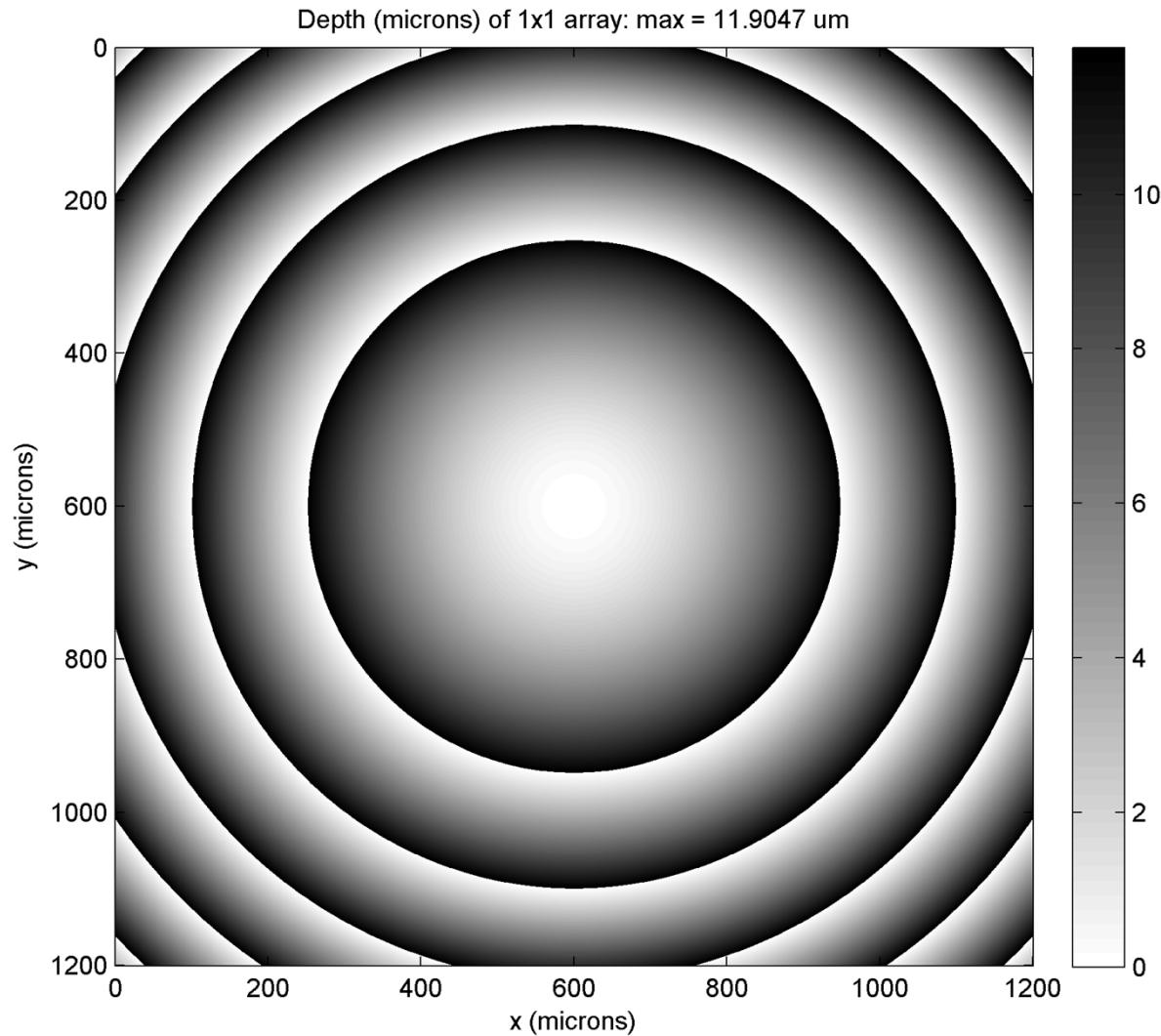
Telegraph noise power spectrum density



- PSD form time series noise comparable to measured noise
- As predicted is the major noise source (> phase noise due to offset charges, > amplifier noise)

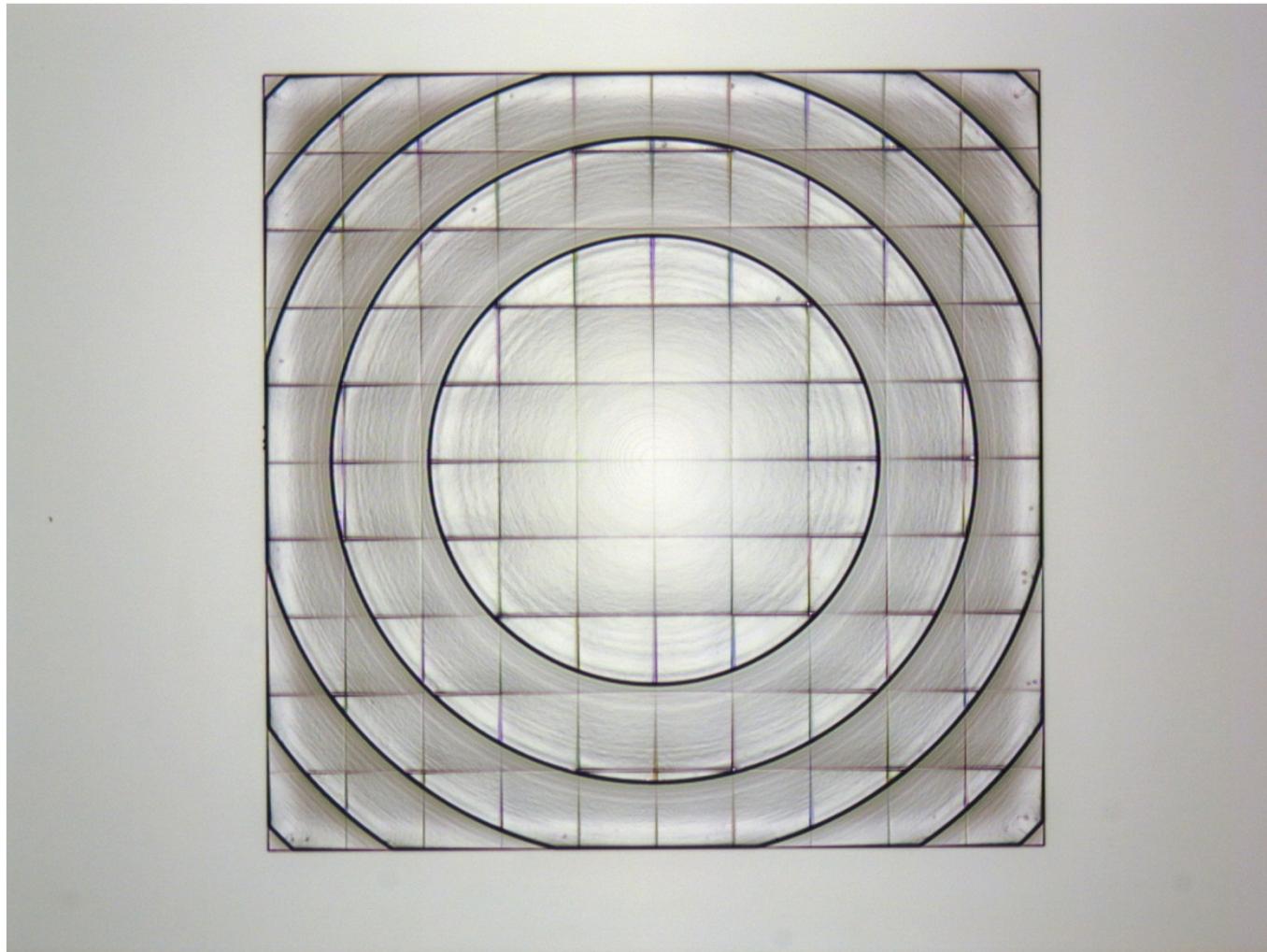
Fresnel lens development - Design

$\lambda = 200 \mu\text{m}$, focal length = 1 mm in $n_{\text{Si}} = 3.4$



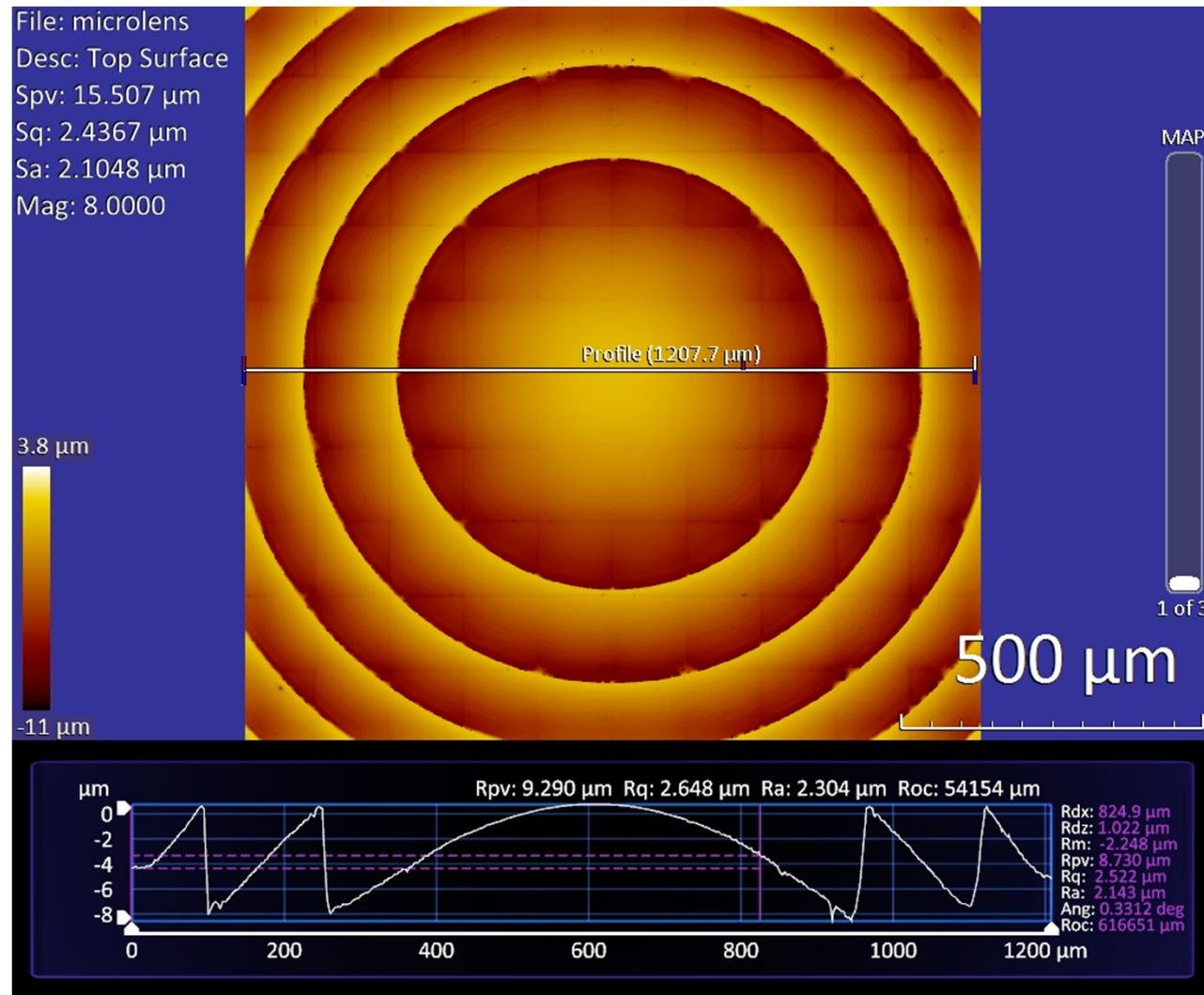
PMGI Resist Photos

Lens depth ~9 μm (a couple microns shallow)



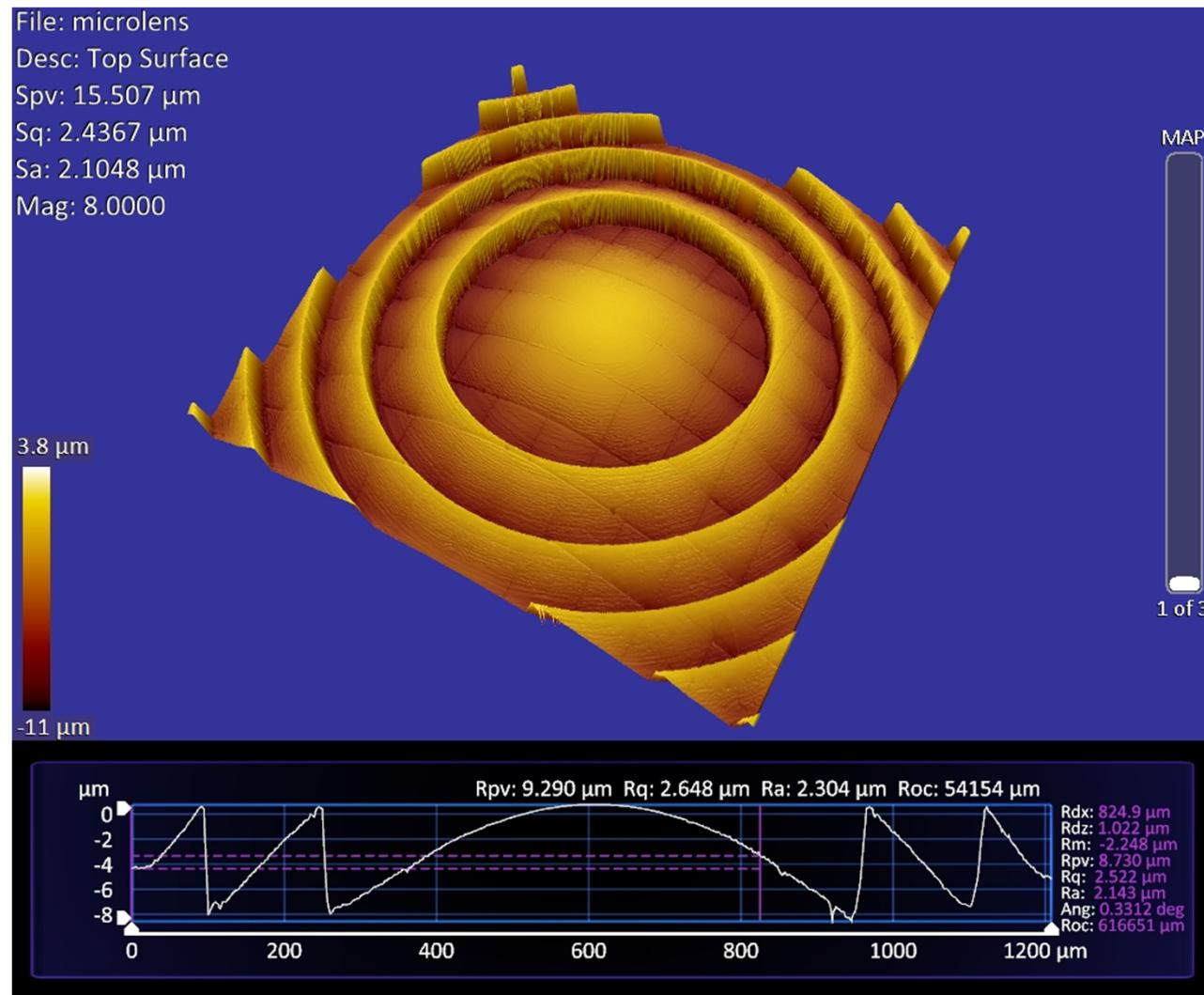
Resist Surface Profile

Taken during Zygo ZeMapper demo



Resist Surface Profile

Taken during Zygo ZeMapper demo





Conclusion

- Achieved $1 \times 10^{-19} \text{W}/\text{Hz}^{1/2}$ at $2 \times 10^{-20} \text{W}$ with $200\mu\text{m}$ wavelength
- Telegraph noise measurements provide additional information
- Improvements
 - Improve resonator response
 - redesigned resonators
 - If resonators are close to ideal (9dB), NEP in $10^{-20} \text{W Hz}^{1/2}$ range!
 - Lower number of residual quasiparticles
 - increase island gap with respect to reservoir
 - better shielding/ filtering
- Fresnel lens development progressing well